CIRP Annals - Manufacturing Technology 72 (2023) 673–696

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: https://www.editorialmanager.com/CIRP/default.aspx

Sensor and actuator integrated tooling systems

F. Bleicher (2)[a,*], D. Biermann (1)[b], W.-G. Drossel (2)[c], H.-C. Moehring (2)[d], Y. Altintas (1)[e]

[a] Institute of Production Engineering and Photonic Technologies, TU Wien, Austria
[b] Institute of Machining Technology, Technische Universität Dortmund, Germany
[c] Fraunhofer Institute for Machine Tools and Forming Technology, Chemnitz, Germany
[d] Institute for Machine Tools, Universität Stuttgart, Germany
[e] Department of Mechanical Engineering, University of British Columbia, Canada

A R T I C L E I N F O

Article history:
Available online 8 August 2023

Keywords:
Machining
Tooling
Sensor
Actuator
Integration
Control
Smart tool

A B S T R A C T

The advances in electronics, sensors, actuators, smart materials, computers, and communication technologies led to new and improved mechatronics-based smart tooling systems. This paper reviews the sensors and actuators used in tooling systems. The sensor principles to measure force, displacement, and temperature are explained. Actuators based on piezo, magnetorheological fluid, shape memory alloy, and magnetostrictive principles are discussed. Wireless and wire-based power supply and signal transmission techniques to stationary and rotating tools are described. The integration of sensors, actuators, power supply, and microcontrollers to various tooling systems used in boring, milling, turning, and grinding operations are presented along with their process monitoring and control applications in the industry. It is shown that the sensor-actuator tooling systems improve the accuracy, robustness, and productivity of machining which adds intelligence to the machine tools. The current challenges include widening the operating bandwidth of tooling systems, wireless power and high-speed data transmission, miniaturization of actuators and sensors, and onboard processing using embedded micro-controllers.

1. Introduction

Machining operations are widely used in industry to give the final shape to the parts. Faster development of products with steadily increasing complexity and accuracy, the use of new materials either classically or additively fabricated, together with shorter product lifecycles lead to significant challenges in production systems [157]. Sensor and actuator-integrated tooling systems can help to meet some of these needs [278]. In the last decade, the number of scientific publications per year shows a significant increase which emphasizes the current importance of research in sensor and actuator-integrated solutions.

In contrast to previous publications like Möhring et al. [187] on autonomous manufacturing systems or Teti et al. [251] on process monitoring, this keynote paper focuses on the technological level of existing sensor and actuator technology and their integration into tooling systems. In addition, the peripheral and auxiliary systems for signal and power transfer, signal acquisition, processing, and decision-making are included. The paper mainly focuses on the discrete workpiece machining processes with geometrically defined and undefined cutting edges. Sensor-integrated tools were considered by the CIRP keynotes in the past. Micheletti et al. [175] showed the application of tool wear sensing, while Tlusty et al. [254] covered the use of force and vibration sensors to assist unmanned machining operations. Tönshoff et al. [256] presented the application of sensors on machining process monitoring and control. Byrne et al. [45] and Teti et al. [250] focussed on tool condition monitoring and decision making. This paper, however, presents the direct coupling of sensing and signal processing methods with actuated tooling systems. The sensor and actuator integrated tooling lead to mechatronic or adaptronic systems that can autonomously monitor and control machine tools and machining processes, respectively. The sensory feedback is used by the monitoring and control algorithm, which sends control action to the CNC via integrated communication interfaces leading to closed-loop machining. These applications cover process assistance, compensation of static, dynamic, and thermal deformation errors, as well as monitoring of tool wear and breakage. Actuators in tooling systems such as fast tool servos can be used for the precision machining of parts with non-symmetric contours, surface textures, or the compensation of dynamic tracking errors. Neugebauer et al. [195] and Drossel et al. [76] overviewed such mechatronic systems employed in the manufacturing industry. The actuated tools can be used for (i) process assistance, (ii) process adaption to compensate for deviations or to actively adjust the process behavior, and (iii) closed-loop control of the tool motion relative to the workpiece. Besides active systems, semi-active approaches also exist to damp the structural vibrations which improves the chatter resistance, hence the metal removal rate [192].

The paper is structured as follows. An overview of sensors and actuator technologies with their operating principles is presented in Section 3. The integration of data and power transmission methods in tooling systems are given in Section 4 followed by the signal processing and control techniques in Section 5. Section 6 summarizes the

* Corresponding author.
E-mail address: bleicher@ift.at (F. Bleicher).

https://doi.org/10.1016/j.cirp.2023.05.009
0007-8506/© 2023 Published by Elsevier Ltd on behalf of CIRP.

research applications in the field of sensor integration, and Section 7 covers the use of actuators in tooling systems. The emerging technology trends are discussed in Section 8. The paper is concluded in Section 9.

2. System design and architecture

Sensors and actuators used in tooling systems require both, physical and digital integration. Systems like sensor-integrated milling heads [185], the projects SmartTool [3,112,221] or BaZmod [139], and adaptronic systems [76] address both the physical world and the digital surroundings, forming a cyber-physical production system (CPPS) [103,159]. Yao et al. [293] described the structure of CPPS with its real-time data processing, reconfigurability, interoperation, decentralized decision-making, intelligence, and proactivity capabilities in manufacturing. The recent trend is to use the digital twin's (DT) conceptualization, systematization, construction, and adaptation properties to form CPPS. DT can be defined by the integration of the digital model and the digital shadow of a system as described by Aheleroff et al. [8]. While the digital model has no continuous connectivity with its physical counterpart, the digital shadow is interconnected via at least a unidirectional automated data flow from the real to the virtual system. In terms of manufacturing, Negri et al. [193] and Teti et al. [251] defined DT as the virtual representation of a production system by mathematical models executed on different simulation disciplines and having bidirectional connectivity. The data exchange needs bidirectional real-time connectivity [8]. Physical control (edge) and cyber control (data aggregation, models, fog, cloud) layers are connected using analog or digital interfaces and industrial networks based on protocols like OPC Unified Architecture (UA) [198] or MTconnect [191]. Thereby, sensor-integrated tooling systems with the data acquisition functionality collectively recreate the real-world manufacturing environment in cyberspace, supply the relevant knowledge by fused sensor data, and drive high-level cognitive tasks by perceiving, monitoring, understanding, predicting, and deciding the right course of action for adaptive machining processes [9,143,187]. As such, a DT incorporates data analytics, artificial intelligence (AI)-based modeling, simulation, and visualization for decision-making. It follows that the design and selection of the appropriate sensing and data analytics hardware and software is a crucial building block for the development of robust and high-performance digital twins [238]. Fig. 1 depicts the interaction of physical and virtual components. Like in [45], DT learns from real-time sensory data for forecasting the future of the corresponding physical process. Due to the model's computational complexity, fast algorithms are derived and integrated into edge-computing devices allowing for real-time process control at very short latency. The real-time capability considers data transmission in time and frequency domains as well as their analysis through feature extraction and decision-making [34,91]. By the paradigm of collaborating computational entities, which are in connection with the physical world, data-processing services evolve smart processes [57,147] and release autonomous machining functionality [151].

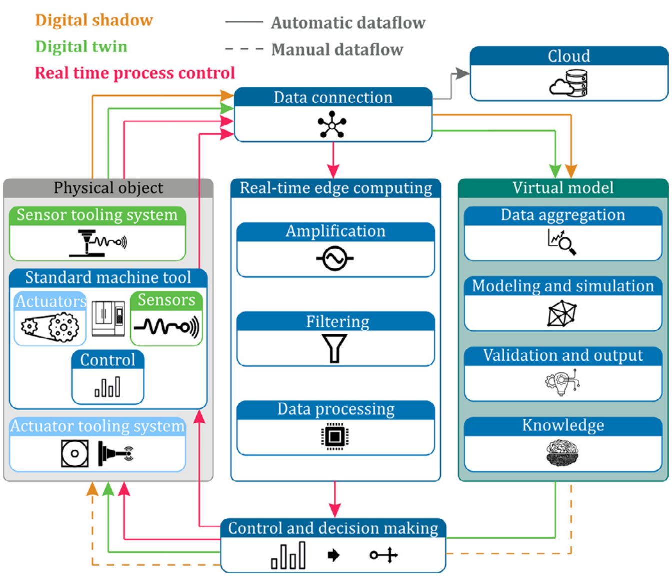

Fig. 1. Physical and virtual processes [106,143].

The connectivity of sensor-integrated smart tools is the basis for providing real-time feedback about the machining process as close as possible to the tool engagement point. Process and tool condition monitoring require continuous measurement of physical process parameters like cutting forces, temperatures, or vibrations. In many reported applications, a combination of sensors is used [165,255]. For multivariable integration, the state space representation can be chosen to describe the controlled system [80].

Sensor and actuator-integrated tooling systems are categorized according to their applications in manufacturing. When the sensor signals are used only for monitoring applications, integration to the controller is not needed [183]. For instance, Negri et al. [193] compared the roles of sensors in the context of CPPS. Machine-learning algorithms are used to require knowledge from historical sensor signal datasets. Extracted features and derived algorithms for real-time edge computing seamlessly interact with the real machining process accommodating the data transmission and evaluation of delay. The digital interface requires not only the firmware integration of the component but also communication structures by information and communication layers [57,237].

In modeling, the black box (without any knowledge of the internal operation), grey box (theoretical data sets are used to complete its model), or white box (fully described) approaches are employed [83]. Neugebauer et al. [195] described adaptronic systems as the functional enhancement of machine tools by adding electronic components, sensors, and actuators to the mechanical structure. The scope of actuator-integrated tooling systems incorporates the real-time capabilities of adaptronic systems and enables autonomous functionality in process adaption. These functions are classified as open and closed-loop adaptronic solutions with different designs as shown in Fig. 2.

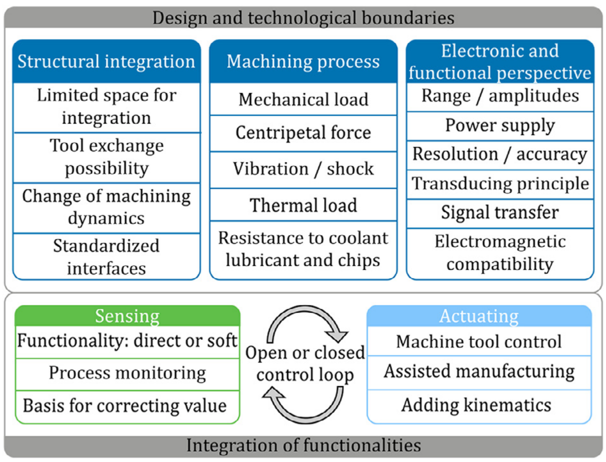

Fig. 2. Design and technological boundaries for physical integration.

In most machining applications, sensors and actuators are integrated into rotary tooling systems. Besides the static and dynamic loads like process forces, vibrations, and centripetal forces, the resistance to coolant and chips plays an important role. Wireless power supply and data transfer are important subsystems. The resolution, the communication range, and the use of standardized interfaces and protocols are considered in data transfer. The challenge of integration in tooling systems is the limited space. Besides the design considering technological boundaries, integrated functionalities and thus the available room for various solutions permit the classification and distinction of different applications. Actuators can be utilized to compensate for distortions [196] and vibrations [272], and enable a wide range of closed-loop control functionalities, which are used to optimize machining operations. Actuated tooling systems are beneficial for the reduction of cycle time and increased material removal rate, for machining parts with complex geometries [96,98] or to mitigate process uncertainties [61,63]. The latter, e.g., workpiece material properties, can not be precisely predicted ahead of time by only relying on model-based descriptions. However, the use of sensor information and the ability to adapt and adjust itself without intervention by the operator helps to improve the performance concerning part quality and accuracy, process stability, resource efficiency, and productivity [78,148,196]. The integration of actuators into the tool enables vibration-assisted machining, e.g., of brittle materials, thereby reducing process forces, and allowing chip separation ([99], see Section 7).

The limited available space for the physical integration of sensors and actuators is depicted in Fig. 3. Both, integrated sensors and actuators require signal transfer and power supply units. The tooling system consists of a mechanical interface to the main spindle, such as the tool holder and its clamping device in the spindle shaft. In monolithic tooling systems, the tool body, tool shank, head, and holder are integrated into one piece. Usually, the tool holder is deployed as a separate subsystem of the tool system. Inserts, milling heads and drills, etc. represent the cutting tool, and they are clamped in the tool holder or the tool body via mechanical interfaces. The limited space for integration becomes more restricted due to coolant supply via internal channels and standardized tool interfaces.

A classification by the spatial integration possibilities can be realized considering four sub-areas as illustrated in Fig. 3.

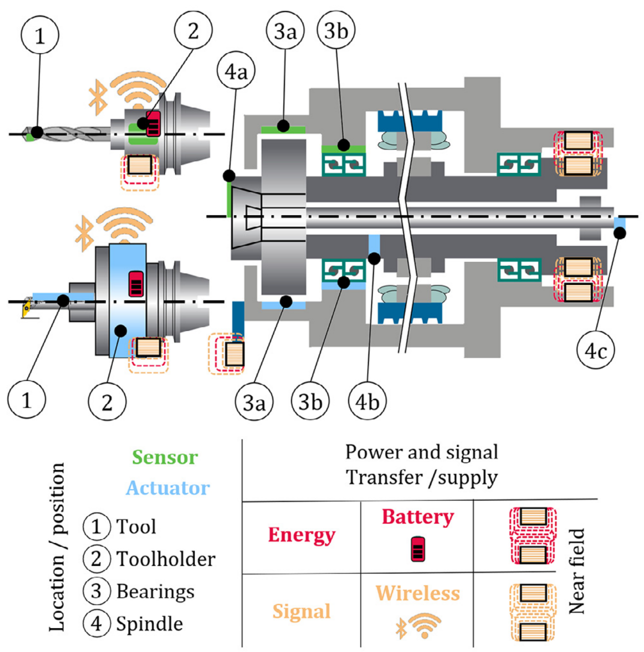

Fig. 3. Possible positions for sensor and actuator integration.

A first implementation option of sensors or actuators (see position 1 in Fig. 3) employs the tool body and the cutting tool. This area offers the advantage of being very close to the cutting point, but also entails a very limited installation space. High mechanical and thermal loads, cutting fluid, and chip impact must be taken into account when designing the cutting tool and holder integration. The second option considers the rear part of the tool body or tool holder (see pos. 2). The standard tool holders are used with modifications such as holes and pockets [34,300]. Some of these solutions need attachment structures for signal and power transfer, which require additional installations in the workspace envelope and an automatic tool change may not be possible. The third integration considers the implementation of sensors or actuators in the bearing or guiding systems of the rotating spindles (see pos. 3). By attaching designed components or mountings for the integration of sensing and actuating principles, the spindle shaft connected to the tooling system can be affected [153]. This spindle shaft integrated sensor (see pos. 4) has disadvantage of being away from the cutting point on the tool, but offers more space for integration. Apart from the tooling system, sensors and actuators can also be installed in the machine structure or on the workpiece [64,250,251]. These methods can have similar functionalities and operating principles but are excluded from the scope of this paper.

3. Sensors and actuators for tooling systems

Transducers act as the interface between electrical and other physical domains in the monitoring and control of machining processes. Sensors convert physical values into electrical signals, while actuators convert electrical signals into physical actions. The following section describes the principles of sensors and actuators, and their integration into tooling systems.

3.1. Measurement principles for the use in tooling systems

The main sensors used in tooling systems are force, torque, displacement, acceleration, and temperature sensors. This section discusses the principles of these sensors and their advantages and disadvantages.

Force/torque, displacement: The measurement of forces or moments can be converted into the displacements provided and that the elastic force-deformation relationship is known. Solutions that do not reduce tool stiffness are preferred. The most commonly used force sensors are resistive strain gauges such as metallic and semiconductor types [239]. Metallic strain gauges are based on the changes in the resistance of an elastically deformed metallic conductor. These gauges consist of a carrier material and a metallic measuring grid. The semiconductor type is based on the piezoresistive effect, which leads to a change in resistance [137]. Semiconductor strain gauges have a sensitivity that is up to two orders of magnitude higher than metallic gauges, however, they are nonlinear and are significantly more temperature sensitive and difficult to compensate than metallic gauges [107]. Strain gauges are applied to the structure by adhesive bonding which has a direct influence on the elongation resistance. The thickness of the adhesive film also influences the measurement accuracy [243]. The interface between the substrate and the measured object is the limiting factor that affects mechanical and thermal strength.

One possibility for the non-contact measurement of displacements is the use of electric and magnetic fields. The most relevant representatives of this class of transducers are based on the variation of capacitance, eddy current or magnetic fields. The advantage of this sensor class is its high sensitivity and capacity for non-contact measurement. However, these sensors are sensitive to tilting with respect to the measured object and thus require precise alignment. Furthermore, the measuring principle results in sensitivity to external electric and magnetic fields, as occurs in spindle motors or inverters [104].

Piezoelectric force sensors are based on a shift in charge within the deformed crystal lattice structure under a load. The degree of deformation is negligible to affect the dimensions of the tool. In an unloaded state, the positive and negative centers of charge are congruent. An external load shifts these centers and creates a measurable shift in charge. Piezoelectric elements can therefore be regarded as direct force transducers, which gives them an advantage over strain gauges. However, the generated charge is volatile, which makes static measurements impossible. Piezoelectric force sensors are generally preferred for measuring high-frequency signals because reducing the lower cut-off frequency requires substantial effort in terms of isolation and charge amplification. Piezoelectric sensors can be integrated into tooling using a variety of methods. These include patch bonding, thick film printing, and vacuum deposition processes for the production of thin films [79,119]. Piezoresistive sensors are also used to measure force directly. The piezoresistive-type of sensors, in contrast to piezoelectric counterparts, can measure the quasi-static forces. Thin films based on diamond-like carbon offer good tribological properties, making them suitable for the direct measurement of rolling element loads in bearings [225]. The disadvantage of these sensors is that they are highly temperature sensitive and therefore require thermal compensation [28]. Table 1 provides an overview of different principles to measure force or displacements.

Table 1
Force/displacement sensors [102].

Type	Electrical value	Order of magnitude sensitivity V/με
Metallic strain gauge	Resistance	10^{-6}
Semiconductor strain gauge (piezoresistive)	Resistance	10^{-4}
Carbo-nano tubes	Resistance	10^{-3}
Piezoelectric	Charge	1
Capacitive	Capacity	10^{-3}
Inductive	Inductivity	10^{-3}

Fiber Bragg grating (FBG) sensors: Sensors based on the FBG principle can be used to measure temperature, mechanical stress, or strain. These sensors consist of an optical fiber with inserted eponymous grating. This grating acts as a narrowband filter that only reflects light that has a very limited spectral width around the Bragg wavelength. Thermal or mechanical deformation of the optical waveguide causes a deformation of the grating and thus a shift in wavelength that can be measured by an optical interrogator [48,218]. For this purpose, both the reflected and the transmitted spectrum can be considered (Fig. 4).

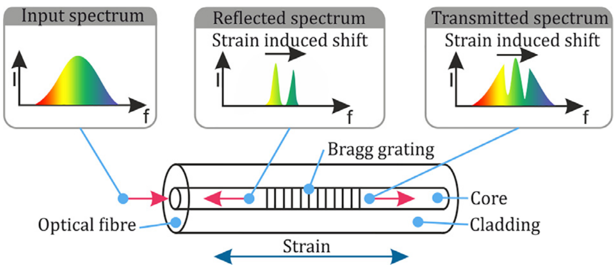

Fig. 4. The working principle of fiber Bragg grating sensors - the reflected spectrum is shifted to a higher wavelength [176].

This measurement principle allows deformations to be resolved in the range of less than 1 µm and therefore, it is suitable for the use in very rigid structures such as cutting tools and machine tool structures [92,218]. Further advantages include the robustness against temperatures (>1000°C) and corrosive environmental conditions as well as immunity to electromagnetic interferences. The disadvantages are the high costs, the bulkiness of the required measurement technology, and its complex installation [218].

Temperature measurement: Temperature can be measured either invasively (i.e., by direct contact between the transducer and the measured object) or non-invasively, without contact. Invasive temperature measurement can be achieved through physical principles such as the thermal expansion of materials, the change of resonance frequencies of crystals, or the thermoelectric principle.

Thermoelectric transducers are particularly relevant for the use in tooling systems because they enable simple evaluation via voltage or resistance measurement. These transducers can be subdivided into thermoelectric generators, resistance, semiconductor, or capacitive sensors [55]. Fiber Bragg grating and surface acoustic wave sensors can also be used to determine temperature. Thermoelectric transducers and their characteristics are summarized in Table 2.

Table 2
Thermoelectric transducers [55].

Type	Sensitivity	Temperature range (°C)
Thermocouples	15 - 250 µV/K	−270…3000
Platinum resistor	400 µV/K	−50…500
Diode	2.5 mV/K	−250…175
PTAT (proportional to absolute temperature)	10 - 110 mV/K	−55…150

Acceleration measurement: The measurement of acceleration and vibration is mostly done using MEMS (micro-electro-mechanical systems). The operating principle of these transducers is based on a mass, which experiences a force due to the measured acceleration. The force can be determined either directly by piezoelectric sensors or indirectly via the deformation of a spring element. The indirect methods can be based on resistive or capacitive effects, analogous to force and displacement measurement [23]. The sensors are selected in the same way as force transducers. Capacitive and resistive sensors are suitable for static measurements; very high accelerations or high frequencies require the use of piezoelectric sensors, although this entails compromises in terms of lower cut-off frequency and resolution. Table 3 shows an overview of accelerometers.

Table 3
Types of MEMS-based accelerometers, parameter ranges based on 118 commercially available sensors [23,84].

Type	Operating temperature (°C)	Frequency (Hz)	Acceleration (g)
Capacitive	−40…85	$0…10^3$	$\pm 10^3$
Piezoelectric	−74…200	$1…20{\cdot}10^3$	$\pm 10^6$
Piezoresistive	−20…85	$0…5{\cdot}10^3$	$\pm 10^5$
Resistive	−20…85	$0…5{\cdot}10^3$	$\pm 10^5$

Surface acoustic wave sensors: The use of surface acoustic waves (SAW) enables the contactless measurement of a wide range of physical and chemical quantities. Piezoelectric substrates can be used to convert radio waves into SAW. A fingerlike conductor structure is applied to the substrate (interdigital transducer - IDT). The SAW continues along the surface of the substrate and can be converted into a radio wave by an IDT. The wave can be reflected via a grating and only one IDT for transmission and reception, or another IDT can be used (Fig. 5). Mechanical and chemical influences on the propagation path cause changes in velocity, amplitude, and wave phase, which makes them measurable. This allows for the design of non-contact passive temperature and deformation sensors [248]. Investigations during turning and broaching showed that SAW sensors could provide in-process strain measurements of similar quality to those of conventional strain gauges [241]. However, the temperature influence on the measurement signal can be greater than the strain influence by a factor of 40. When SAW sensors are used under fluctuating ambient temperatures, suitable compensation mechanisms must be considered [126].

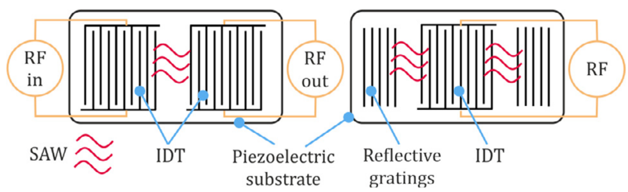

Fig. 5. Structure of SAW sensors; left: dual IDT setup, right: one IDT with reflective gratings [248].

3.2. Actuating principles used in tooling systems

The use of actuators in tooling systems places special demands on the specific power density. Depending on the application, the maximum operating frequency has a different significance. If, for example, only an exact adjustment of the cutting edge is required before boring operations, it can be done relatively slowly. However, if a non-circular cross-section is to be cut, the positioning frequency must be higher than the rotational speed of the tool; hence, the actuator must have high bandwidth. The power density shown in Fig. 6 can guide the initial actuator selection.

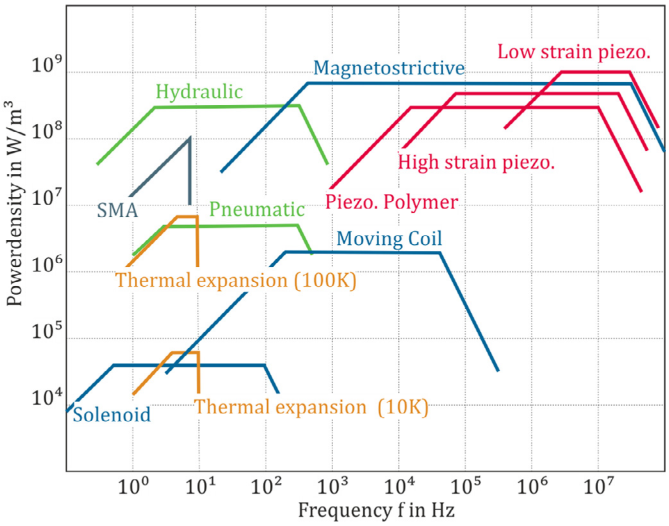

Fig. 6. Volumetric power density and frequency range of different actuator principles [125].

The miniaturization of conventional mechatronic actuators leads to unfavorable scaling effects caused by the physical operating principles and the necessary guide elements. For example, the force of electromagnetic actuators scales with the fourth power of size [51]. Actuators based on active material principles, such as piezoelectric or shape memory actuators, are one way of circumventing these scaling problems. Since forces and displacements are directly proportional to the size, additional guide elements can be designed [202].

Research and development in recent years has made it possible to further miniaturize the actuators while maintaining almost the same work density. In this context, smart materials such as shape memory alloys (SMA) or piezo elements still exhibit high volumetric work densities even in very small dimensions as depicted in Fig. 7 [211].

Volumetric work density is defined as the ratio of work the actuator can perform per stroke to the volume of the actuator. It should be noted that the necessary supply of energy and working media worsens power density. Hydraulic and pneumatic actuators are not generally suitable for integration in tooling systems except for special microhydraulic actuators, e.g., the use of a miniature piezo hydraulic pump [108], elastic fluid filled actuators [111], or piston-cylinder micro-actuators [271]. Another option would be to use the central supply of cooling lubricant or compressed air as an energy source, as is the case for HPC spindles [227].

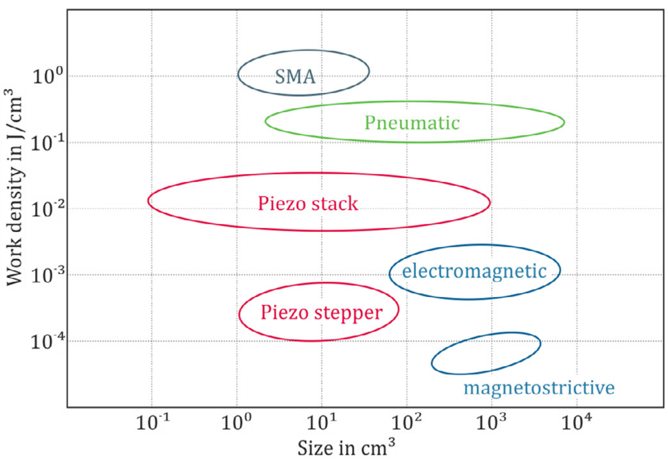

Fig. 7. Volumetric work density of different actuator types [211].

Piezoelectric actuators: The piezoelectric effect can also be used to design highly rigid actuators by generating a crystal deformation via an applied electric field. This class of actuators can be grouped under direct-drive, mechanically amplified, and stepper drives. In contrast to direct-drive piezo actuators, which only use the stroke of the piezo material itself and thus allow very short travels with high forces, the amplified drives use mechanical leverages as illustrated in Fig. 8. These mechanisms increase the stroke at the expense of the blocking force [279]. Stepping drives or piezo motors enable a continuous process. This can be achieved by using a feed clamp mechanism, friction, and inertia or by ultrasonic drives [178,279]. In addition to precision positioning applications, piezo actuators are particularly suitable for ultrasonic vibration-assisted machining and grinding due to their high operating frequencies. Such systems are mainly designed as resonant oscillators to exploit the effect of amplitude amplification [294].

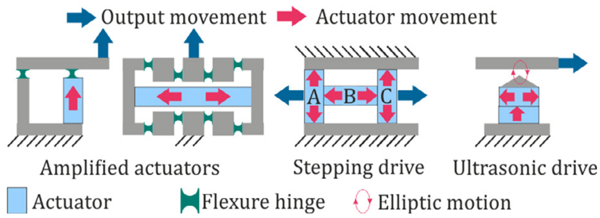

Fig. 8. Amplified piezoelectric actuators, piezo stepping and ultrasonic drives [279].

Magnetorheological fluid-based actuators: Magnetorheological fluids (MRF) are suspensions of a non-magnetic liquid such as silicone oil and a strongly magnetic micrometer-fine solid powder. When the liquid is exposed to a magnetic field, these particles align along the field lines and increase the apparent viscosity to such an extent that it becomes a viscoelastic solid. The yield stress of the fluid can be controlled by several orders of magnitude, requiring field strengths with magnetic flux densities in the range of 1 Tesla. Magnetorheological fluids can be used to adjust stiffness or damping and are thus used in designing brakes, clutches, and shock absorbers [268]. MRF actuators can be classified as a valve, shear, or squeeze type, depending on the load case (Fig. 9).

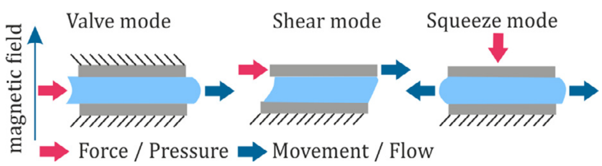

Fig. 9. Operational modes of MRF devices [268].

Shape-memory alloy: SMAs are metallic functional materials that can exist in different crystal structures such as austenite, twinned martensite, and detwinned martensite. During the reversible transformation between martensite and austenite, the neighboring relationships in the atomic bond are maintained. This provides the eponymous shape memory effect, in which the material seems to remember its initial shape after apparent plastic deformation and subsequent heating. It is also possible to influence the orientation of the martensite using magnetic fields (ferromagnetic shape memory alloys - FSMA). Both thermal and magnetic effects result in macroscopic stroke which can be used to design actuators [75]. However, a disadvantage of thermal SMAs is that they have low operating frequencies since they are subject to relatively slow cooling processes. This particularly applies to high-load actuators, which, in contrast to the widely used wire actuators, have a larger cross-section that allows them to achieve higher actuating forces [168]. FSMA actuators consist of single crystals, which are difficult to process mechanically and which limit the field of application. Furthermore, the required magnetic flux densities result in large energy and space requirements for the magnetic circuit [129,194].

Magnetostrictive actuators: If an external magnetic field is applied to a ferromagnetic material, the Weiss domains align themselves in the same direction. This rotation of the dipoles results in a macroscopic deformation of the material, which can be used for the design of actuators [121]. In terms of actuator stroke, such actuators are comparable to piezo drives, but the usable bandwidth is two orders of magnitude smaller [210]. Nevertheless, direct, mechanically amplified, and resonant actuators can be designed just as with piezo drives [18]. However, like FSMA, these actuators have the disadvantage of requiring additional installation space to provide the necessary magnetic fields. With about 25 to 80 kA/m, the required field strengths are much lower than those required for FSMA, with >300 kA/m [118,131].

Electromagnetic actuators: Electromagnetic actuators can be classified depending on whether they are based on the Maxwell or the Lorentz force. Lorentz force-based drives include electric motors such as synchronous and asynchronous machines. The combination of a coil and a concentric permanent magnet results in a moving magnet and moving coil/voice coil actuators, depending on the moving part. These actuators allow high power density at medium to high frequencies [242]. Actuators based on the reluctance principle caused by Maxwell's force, such as solenoids, deliver small strokes with short response times, e.g., in injection nozzles of common rail diesel applications with a switching time of 0.3 ms at a stroke of 0.1 mm [242]. Because the magnetic field is current driven, electromagnetic actuators have low efficiency [125]. In combination with the high inductances, this places high demands on the power supply. Furthermore, the heating of the coils limits the miniaturization potential [51]. Table 4 shows a comparison of different actuators.

Table 4
Comparison of actuator principles [90].

Type	Stroke/length ratio (%)	Work/volume (J/m^3)	Dynamic range (Hz)
Direct piezo	≤ 0.1	$\leq 10^5$	10^6
Piezo stepper	~ 50	$\sim 10^4$	*
SMA	~ 5 **	$\leq 2{\cdot}10^7$	< 100
FSMA	5 **	$\leq 2{\cdot}10^5$	10^3-10^4
Solenoid	≤ 10	$\leq 10^5$	$< 10^3$
Voice coil	~ 50	$\sim 10^4$	*
Electrostatic	≤ 0.3	$\leq 4{\cdot}10^3$	10^5
Magnetostrictive	≤ 0.2	$\leq 4{\cdot}10^4$	10^4

* Depending on stroke, max. load free acceleration < 20g.
** With a higher stroke, the service life is reduced [133].

4. Power and signal transfer

The transfer of energy and data is essential but challenging for rotating tools. Several supply options for data and energy are presented in the following section.

4.1. Power supply for sensors and actuators in tooling systems

Various types of energy supply can be used for rotating tool systems. These include inductive energy transfer, energy storage systems with rechargeable or non-rechargeable batteries, or energy harvesting. The choice of energy supply depends mainly on the energy requirement. While sensory tooling systems usually require a few watts or even less, actuator systems sometimes need several hundreds of watts. In some cases, high energy requirements for rotating tools can be achieved via electrical slip rings. Slip ring solutions can also be used for data transfer [273] and for combinations of data and power transfer [4,61]. Accelerated wear of slip rings and disturbances are observed, particularly at high rotational speeds and in the machining area with abrasive media. Inductive power transfer may be less fragile due to the contactless transfer with an enclosed casing. The inductive system consists of a primary stationary and a secondary rotating coil. The coils magnetically couple via ferromagnetic cores and an air gap. Therefore, an alternating current in the primary coil leads to an alternating magnetic field and thus to an induced voltage in the secondary coil. The required dimensions of the coil pairs in inductive coupling are estimated using the design process proposed by Silge [99,232]. Inductive power transfer can be classified according to the orientation of its air gap [260]. Thus, there are cylindrical air gaps (radial pitch) [40] and plane air gaps (axial pitch) [117,180]. Fig. 10 shows the different types of inductive energy transfer.

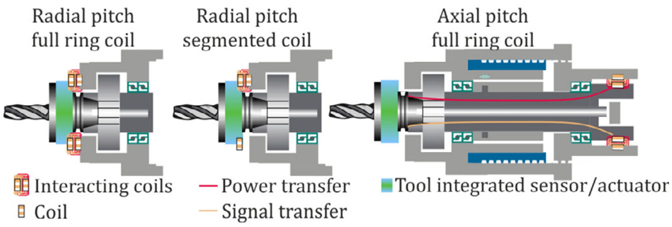

Fig. 10. Possible configurations of inductive power transfer for rotational tooling systems.

The overlap of the coils can be further differentiated into full rings and the combination of a full ring and a ring segment with the possibility of having varying transformer positions. Often, the secondary coil is permanently installed in the tooling system and the primary coil is placed at the machine tool spindle. In other solutions, both coils are installed in the tooling system, with the primary coil mounted on the rotating tool and supported against rotation at the spindle. Another solution realizes the special HSK-i interface, where the power transfer system is located inside the main spindle, and the contact with the tool holder is made via pogo pins, as shown in Fig. 11 [233,269].

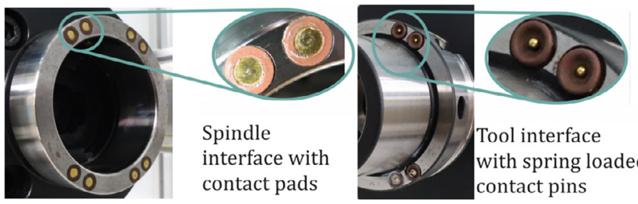

Fig. 11. HSK-i interface with electrical power and data transfer [139].

Radio frequency identification (RFID) technology [77] is an alternative method for transferring energy to the sensory tooling system. The inductive energy transfer systems consist of cores with gaps which can lead to variations in magnetic coupling during rotation causing harmonics in the transmitted voltage. If the transferred voltage is conditioned within the tooling system, such behavior is not critical. In the case of ultrasonic systems, the transferred voltage is used for power supply and simultaneously as a signal for the frequencies and amplitudes to be excited. Here, rotation speed-dependent voltage variations can affect the system.

Battery-based solutions: For sensory tooling systems with low energy requirements, sufficient operating time can be achieved through energy storage. Rechargeable [185,201] and non-rechargeable batteries [39,214] can be used. A commercial example is the Spike tooling system from Promicron, which uses rechargeable batteries for energy supply.

Energy harvesting solutions: Visser et al. [270] considered the possibility of harvesting energy from radio frequencies for low-power sensors. Capacitive energy harvesting transducers (such as Si/SiO_2 - buried oxide/Si substrate) can also be used for energy harvesting. Vibrations from the process are transferred to the transducer and converted into voltage [200]. In addition to providing a general overview of energy harvesting for tooling and sensor systems, Ostasevicius et al. [200] describe the development of a harvesting system based on a piezo transducer as shown in Fig. 12a. The harvester consists of a stack of ring-shaped piezo elements that are located between the tool body and a back mass. Longitudinal and torsional

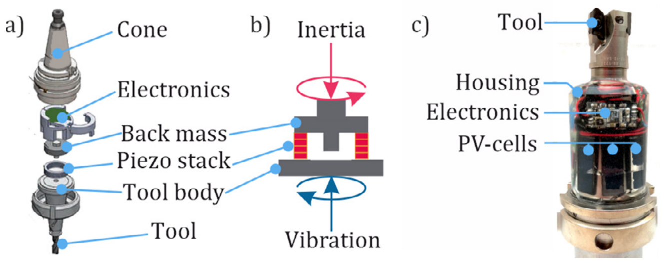

Fig. 12. Tooling systems for condition monitoring using energy harvesting, a) energy harvesting via the piezo transducer [200], b) schematic sectional view of the energy harvester, c) photovoltaic powered sensory milling chuck [97].

vibrations of the tool body cause inertial forces on the back mass. This cyclically loads and unloads the piezo, resulting in the generation of electrical energy. Such systems work most efficiently at resonance [200]. Furthermore, photovoltaic cells can also be used in combination with a rechargeable battery to supply power to a sensor in a tooling system as shown in Fig. 12b.

Power consumption and power modes: In particular, battery-powered and energy harvesting solutions require the use of ultra-low power electronics to achieve long operation periods. In addition to the selection of energy-saving hardware, such as microcontrollers, analog-to-digital converters (ADCs), and voltage converters, the software is also important. The average power requirement can be reduced through the efficient use of different power modes as depicted in Table 5.

Table 5
Power performance characteristics of selected µCs [200].

Controller	Voltage (V)	Current consumption (µA)		
		Active	Stand by	Off mode
MSP-430G2553	1.8-3.6	230/MHz	<0.5	<0.1
ATmega128L	2.7-5.5	1375/MHz	N/A	0.15
LPC111x	1.8-3.6	150/MHz	6	0.22
STM32L4	1.7-3.6	120/MHz	35/MHz	0.33

4.2. Signal and data transmission

Most of the sensor and actuator systems in machine tool applications available on the market use wired Fieldbus systems for data transmission. For rotating tools, however, only slip rings are currently available to connect to Fieldbus. As an example of an interface from the spindle rotor to the tool, the HSK-i interface shown in Fig. 11 includes a data transmission of 10 Mbit/s as well as an energy transmission [269]. Radio transmission systems are also used in data and signal transmission. Electromagnetic interference from drives, other radio systems operating on the same or neighboring frequencies, the metallic environment, and chips as well as extensive use of cutting fluids pose a challenge to the robustness of such data transmissions. Attention must be also paid to energy consumption to enable the continuous operation of the sensor or actuator system. The energy requirement depends on the transmission standard used and on the required range and data rates. An overview is given in Table 6.

Table 6
Power consumption of different wireless standards [128].

Wireless standard	Range (m)	Data rate (kb/s)	Power consumption (mW)
Bluetooth	10	1000	10
Wi-Fi	100	15000	835
ZigBee	100	250	36,9

To reduce energy consumption, it can be useful to perform parts of the data analysis on the sensor node. Instead of transmitting raw data, only the calculated metadata such as FFT or wavelet analyses are transmitted via radio. This approach showed to increase battery life by 43% [122].

Wireless data transfer: IEEE 802.15.4 (low rate WPAN) describes a physical data transmission layer with low overhead. Depending on the implementation (Zigbee, WirelessHART, WIA-PA, ISA100.11a, etc.), low latency and thus high determinacy of the transmission can be achieved. However, the data transmission rate is rather low. On the application layer, WIA-PA and WirelessHart support HRT protocol. WIA-PA is also compatible with Profibus. All implementations support star and mesh network topology [25]. Another standard that uses the same 2.4 GHz band is Bluetooth low energy (BLE), which offers a data transmission rate of up to 2 Mbit/s but does not support limited packet delays and therefore does not allow real-time communication. However, research is underway to enable real-time capability through an additional software layer [152]. An overview of different communication standards is depicted in Fig. 13. Raptis et al. [215] reviewed the data delivery delay and its compensation for data management (coordination and computation of data) in Industry 4.0. Zoppi et al. [301] developed a quality of service (QoS) framework for mitigating end-to-end delay in industrial wired/wireless sensor networks. Mo et al. [177] focused on the performance of the networked control systems (NCS) due to delay and showed how the delay impedes the reliability of NCS. Guck et al. [114] introduced a software-defined networking (SDN)-based function split framework for reducing delay. The SDN-based framework met the end-to-end delay requirements, guaranteeing the real-time QoS of data exchange. Yagi and Sawada [290] articulated that the delay underlying a communication network is random and that it causes instability in the feedback systems. They also designed a Kalman filter to reduce the effect of the random delay. Fan et al. [89] showed that a random delay underlying the NCS degraded the control performance, making the system unstable. They presented a control scheme called networked predictive control to mitigate the effects of transmission delay and to achieve desired control performance using two components: a network delay compensator and a control prediction generator. Wu et al. [287] described sensor-to-actuator and controller-to-actuator delays using Markov chains. They also proposed a control scheme that compensates for the delays and makes the NCS stable. Sun and Huo [246] developed a switching control approach called the Markovian jump linear system. It models the random delays similar to a Markov process and stabilizes the NCS. Guo and Gu [116] described that random time delay is the cause of instability and poor performance in the NCS. They also suggested a model to improve stability. Baillieul and Antsaklis [24] referred to delay as unavoidable and deemed it as one of the challenges of modern networked control systems that are composed of heterogeneous systems and applications. They also mentioned that the sensors might fail to transmit data immediately, and that data loss may occur due to communication delays. Distributed control systems are considered to perform better at overcoming delay-related issues compared to centralized ones. Bijami and Farsangi [31] described that the communication delay

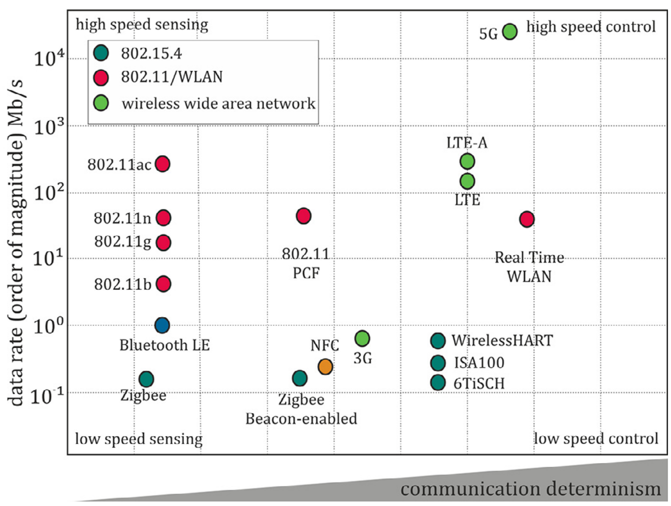

Fig. 13. Comparison of communication determinism and data rate [100,259].

underlying distributed networked systems composed of heterogeneous sub-systems causes random data loss and makes the system unstable. They also developed a control framework for stabilizing the networked systems. Ferrari et al. [91] identified different types of delays in an IoT-based environment, such as end-to-end delay, round-trip-time, and jitter.

These delays cause a low data delivery rate, data loss, and control system failure. The authors provided a hardware-independent methodology for measuring delays in an industrial IoT-based environment. Basir et al. [26] mentioned that fog computing performs better than cloud computing for compensating delay-related issues. They mentioned that the systems and applications in the IIoT need to be delay-aware to limit various types of delays (e.g., processing, propagation, transmission, or computation delay) while achieving real-time communication. Wang et al. [276] emphasized that communication delay needs to be considered when designing controllers to monitor and control NCS.

5. Signal processing and control integration

The machining process and the machine tool performance can be monitored and adaptively controlled by collecting force, vibration, sound, and temperature data from analog sensors mounted on the machine, cutting tool, or workpiece. Information such as feed drive and spindle motor torque, actual position, feed velocity, and tracking errors are collected from the CNC by an ethernet-based communication link provided by the CNC manufacturers. While analog sensor data can be sampled at high frequencies, the CNC data is typically limited to servo loop cycle times, i.e., 1 ms. Fig. 14 shows an overview of process monitoring and control integration [179].

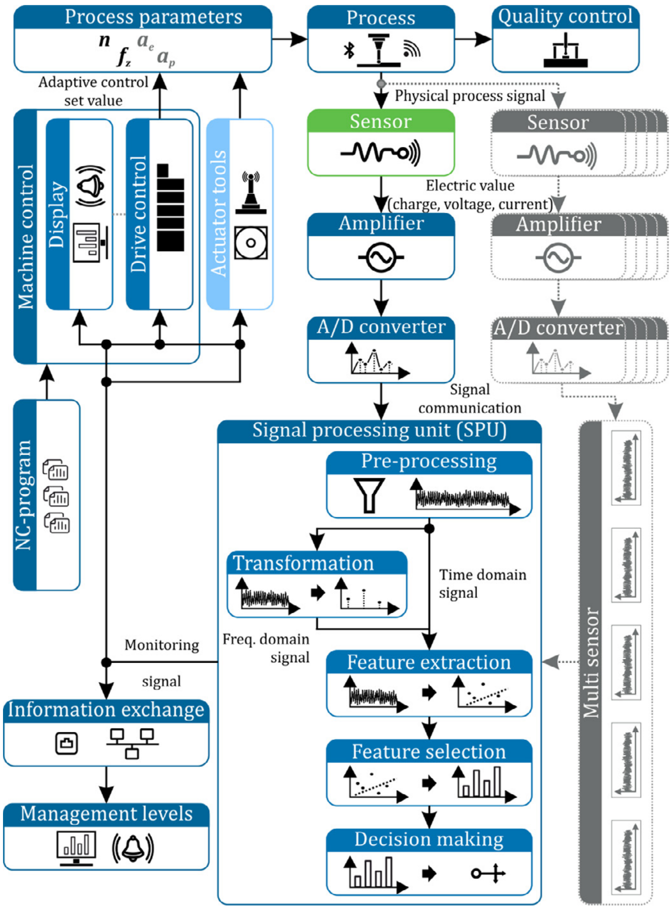

Fig. 14. Overview monitoring and control, based on [179,250].

The NC program is executed by the machine control using the machine's actuators (i.e., drives). Sensors observe the machining process and its physical properties. The process states are collected from the analog sensors, converted into digital data, and processed in the signal processing unit (SPU) [250]. The digital signal is pre-processed and analyzed for feature extraction either in the time domain, frequency domain or in both. On the one hand, feature extraction is used to derive characteristics from the signal. On the other hand, it reduces the amount of data which is particularly advantageous when acquiring raw data at high sampling rates to save memory and, thus, resources.

The gathered information can be provided to the production management and machine operator, e.g., via a display, to initiate corrective actions at the machine or support the production planning. Process parameters can be adjusted via the machine control or actuator-integrated systems, i.e., active tooling systems.

5.1. Signal acquisition

Signal conditioning: Signal amplification can be subdivided into physical quantities to be measured and the used sensor types. Force and acceleration signals are most commonly measured by strain gauge (e.g., [216]) or piezo-based (e.g., [53]) sensors, either incorporating voltage or charge amplifiers, respectively. Also, displacements are measured as physical process signals for direct interpretation or to derive force or acceleration information. For measuring displacements, primarily capacitive, inductive, or eddy current sensors are used in combination with charge amplifiers or resonant circuits for frequency analysis. Moreover, optical sensor systems, e.g., fiber Bragg gratings, are used for displacement, strain, or resultant force and temperature measurement, which transform optical effects (e.g., intensity, phase shift, or modulation) to electric potential and voltage. Thermosensors or thermocouples are mainly used to measure temperature. For acceleration signals, the telemetry associated with the sensor is usually used to amplify the measurement signal [180,184,223]. Choudhury et al. [56] described an online control of machine tool vibration in turning using a closed-loop feedback circuit that measures the relative vibration between the cutting tool and the workpiece. The amplified and phase-shifted sensor signal is fed back to the machining zone with the help of a vibration exciter [56]. Varghese et al. [266] used a telemetric data acquisition module to amplify the acoustic emission signal during grinding and an analog force signal conditioner for their intelligent grinding wheel. In [77], the charge signal of piezoelectric thick film sensors was converted into a charge-proportional voltage. Energy and data transmission was based on RFID technology. Albrecht et al. [11] used a capacitive displacement sensor at the spindle nose of a vertical machining center. Altintas and Park [14] presented the dynamic compensation of spindle-integrated force sensors. The sensor signals were added, passed through an anti-aliasing filter, and then amplified by charge amplifiers. The distortion caused by the structural dynamics of the spindle–holder–tool system was compensated with a Klaman filter, hence the bandwidth was increased [11,14]. Totis et al. [257] showed a sensor-integrated milling tool that was inductively powered. The charge amplifier supplied 5 W power even when the spindle was not rotating. Bretz et al. [39] presented a strain gauge bridge amplification by a programmable signal conditioner. The bridge signal was first subjected to an offset correction. Zhou et al. [300] developed a pre-conditioning module containing an operational amplifier and a terminal adjustable regulator. A charge amplifier was built to increase the lithium battery's voltage to 24 V for accelerometers. An operational amplifier and a terminal adjustable regulator was used to stabilize the accelerometer's output signal. Lou et al. [164] showed a wireless milling cutter system with PVDF sensors and a charge amplifier. Kesriklioglu et al. [136] described a tool-chip temperature measurement using thin-film thermocouples. A four-channel amplifier with built-in cold junction compensation was used to convert the nonlinear signals to an analog output range of 0 to 5 V. Li et al. [154] also presented a tool with thin-film thermocouples. As the oscilloscope's noise was too high, an instrumentation amplifier was adopted. Kerrigan et al. [135] described a system in which the signal of a tool-embedded thermocouple was connected to a thermocouple module which allowed for cold junction referencing, amplification, and filtering of the analog voltage signal.

Analog to digital signal conversion: Analog to digital converters (ADC) from 8-bit up to 24-bit resolutions are commonly used in smart tool applications. Low-pass filters are used to avoid aliasing effects in ADC systems (e.g., [39,94,216]). Luo et al. [164] described a filter to reduce the noise of a force signal. The data was cleaned by circuit interference signal filtering. Because sensors often cannot be connected directly to an ADC, pre-processing is necessary [249]. In [77], the piezo sensor signal was filtered by a second-order Bessel filter. Varghese et al. [266] used a single-pole RC filter for anti-aliasing. The analog signal of the sensory grinding wheel was discretized by 12-bit ADC, and the resulting digital signal was converted to an 8-bit format for interfacing with the data transmission system. In most cases, a resolution of at least 12-bit is required [77,216,220]. Möhring et al. [94,181,184] used a three-channel, 16-bit/channel resolution ADC with an 80 kHz sampling rate to digitize an acceleration signal. Bretz, Abele, and Weigold [2,39] used a 16-bit converter with four input channels at a sampling rate of 250 kHz, giving the three channels a maximum sampling rate of 83.3 kHz to determine the forces via displacements during reaming. Bleicher et al. [34] sampled an acceleration signal of a MEMS-sensor in a tool holder at 9.5 kHz with 16-bit resolution. Öztürk et al. [201] presented a data acquisition with 24-bit high-speed, four-channel simultaneous ADC and a dual-core embedded device running a real-time operating system. The sampling rate could be configured up to 52.7 kHz.

5.2. Signal processing and analytics

Various filters, such as low pass, high pass, band-pass and band-stop filters, are used to extract relevant signal features from sensor data. Furthermore, signal transformations, such as fast Fourier (FFT), short-time Fourier (STFT), wavelet, Hilbert-Huang, and other -transformations are used to convert data for feature analysis. Moreover, observers and Kalman filters were also implemented to remove unwanted noise at high frequencies or between ranges of frequencies. At the same time, the deterministic disturbances can be observed at a specific frequency, e.g., the rotational speed of the spindle shaft. A linear median filter was used by Varghese et al. [266] to suppress the process and sensor noise and thus clearly detect the contact between the grinding wheel and the workpiece. Grabec et al. [109] used a band-stop filter to remove the workpiece rotation frequency from the spectrum of a force signal. Suprock and Nichols [247] presented an analog high-pass filter before the ADC to eliminate low-frequency components under 10 Hz.

Data analysis can utilize conventional statistics or artificial intelligence (AI). Fig. 15 classifies methods for feature extraction, feature selection, and decision-making.

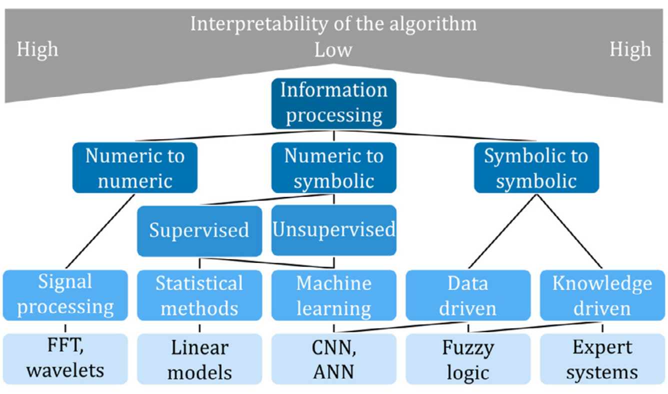

Fig. 15. The landscape of modeling methodologies, based on [158].

An overview of advanced signal processing and decision-making methods was presented in [250,251]. Abele and Bretz [2] deployed the maximum peak force over time to measure the displacement of a sensor-integrated reaming tool. Dini and Tognazzi [72] used the maximum and minimum torque, the mean, variance, standard deviation, skewness, and the distribution density of the torque signal out of the tool holder to monitor the milling process. Rizal et al. [216] utilized the peak-to-peak of a force signal to detect tool wear. Öztürk et al. [201] described a time signal data slicing method for accelerometers to analyze the vibrations and the axial length compensation of the sensor-integrated tapping tool holder. Möhring et al. [180] used the integral of a measured acceleration signal and correlated it to the average roughness value Ra. Bleicher et al. [94] developed an algorithm to search for the highest occurring peaks in a predefined frequency spectrum bandwidth to analyze the stability of milling processes. Caliskan et al. [47] mitigated the forced vibrations by comb-filtering the sound and acceleration signals at spindle frequency harmonics and monitored the energy at modal frequencies using an observer to detect the chatter in milling. Ramsauer and Bleicher [214] described an algorithm that quantifies the fraction of the power caused by uniform cutting to identify single cutting-edge breakage of a milling tool based on acceleration measurements. Cheng et al. [54] converted a force signal with a wavelet transformation to analyze the signal of a sensor-integrated lathe tool holder. To increase the information quality of sensor signals and to reveal process values that cannot be measured directly, observer models can be implemented, which estimate the relevant parameters based on measurable values. Commonly used approaches are the Kalman filter [132] or the Luenberger observer [163]. In [65,240] a disturbance observer was combined with a Fuzzy controller for process control in drilling. The Kalman filter can process analog sensor and CNC data to improve signal quality. The disturbance dynamics along each signal path distort the measurements and limit bandwidth [11,22,205]. Kalman filter was used on current commands to measure the cutting torque indirectly at a higher frequency bandwidth [21,22]. Artificial intelligence (AI) and machine learning (ML) are increasingly applied for data analysis, feature extraction, and selection, as well as decision-making [6]. Monostori et al. [188] gave an early summary of machine learning approaches in manufacturing. Möhring et al. [181] used a convolution neural network (CNN) in monitoring the surface roughness caused by machining. Bleicher et al. [208] used extra trees classifiers for determining edge chipping in milling based on tool holder vibrations. The random forest method was enhanced to find the most indicative features of tool chipping [34]. Another approach involves machine learning and acceleration data to detect chatter in milling [33], including hybrid physics and AI approaches [213]. Aghazadeh et al. [7] employed a CNN with a wavelet packet-based feature extraction for tool wear estimation. Vallejo et al. [263] used an accelerometer, dynamometer, and acoustic emission to analyze the machining process based on the Mel-frequency Cepstrum Coefficients of the short-term power spectrum. The cutting tool condition was modeled with an artificial neural network (ANN). Bretz et al. [39] also used an ANN to determine the straightness of holes created by a sensory reaming tool. Grzenda and Bustillo [113] developed a semi-supervised learning approach to predict the roughness of a milled surface using vibration data. Aralikatti et al. [19] described a rotation forest and decision tree algorithm for carbide tool inserts fault diagnosis using acceleration signals.

5.3. Control and integration in CNC systems

Machine communication for sensor integrated and actuated tools: Several control options exist for actuator-integrated (active) tools (Fig. 14). The output of the signal processing unit (SPU) can be transmitted directly to the active tools (external control) to manipulate the process parameters. Furthermore, the sensor signal can be fed back to the CNC for adjusting the process parameters by changing the feed and spindle speed. Besides proprietary solutions, industrial communication standards were established in recent years, allowing for an integration of sensory and active sub-systems into the machine control environment. Fig. 16 shows the industrial network systems available for internal and external communication with the machine controller based on the study of HMS Industrial Networks (status from 2022). Industrial

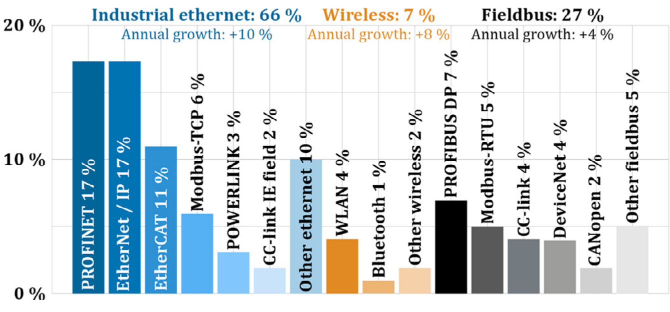

Fig. 16. Industrial networks market shares 2022, based on a study by HMS Networks.

Ethernet and wireless communication standards connect sensor-integrated tools to the machine tool control system. The Fieldbus is still widely used in machine controls for internal communication.

There are three main approaches to data exchange protocols on the market: OPC UA (primarily used in Europe), MTConnect (mainly used in North America), and MQTT [206]. The goal of the OPC (open platforms communication) Foundation [264] was to establish a standard that provides services for reading, writing, and monitoring of control data in automation systems. To avoid the dependency on Microsoft Windows COM/DCOM technologies, OPC Unified Architecture (UA), based on a service-oriented architecture (SOA), was released in 2008 [199]. OPC UA uses web services or a transmission control protocol (TCP) for platform-independent data exchange [110]. The OPC UA server contains the manufacturer-dependent communication protocol to control the machine. The OPC UA client requests the data from the server for application-specific processing [167]. OPC UA TSN (time-sensitive network) is based on a publish-subscribe configuration that enables real-time communication. The server publishes data in intermediate levels, and the clients request data from these levels. The technology can address more than 10,000 network nodes, with scalability from 10 megabits to more than 10 gigabits, allowing it to be used for time-sensitive tasks [42]. The VDW (German Machine Tool Builders' Association) uses the OPC UA standard for its universal machine technology interface (Umati). Umati is designed to make it easier for machines and even plants to communicate with each other or to be integrated into a customer- and user-specific data ecosystem [267]. Like OPC UA, MTConnect is an open data protocol for interoperability between production devices and software from different vendors [191]. MTConnect is based on the extensible markup language (XML) format and the hyper text transfer protocol (HTTP), using a representational state transfer (REST) interface for communication. A large number of tools for implementing MTConnect are available [206]. Secure transmission is possible even in unstable networks. Because of the wide variety of data types for the transition of signals, MQTT (message queue telemetry transport) became one of the most important protocols in the IIoT field alongside HTTP. MQTT follows the publish-subscribe model. The basis is a so-called broker. Each message sent by the publisher has a subject in MQTT. The recipients can subscribe to this subject, and the broker distributes the messages (data) accordingly. TCP on the "Edge" is increasingly used for communication between machine and SPU. The edge computers are directly connected to the machine's numerical control unit (NCU) via ethernet [226] and communicate bi-directionally. Low- and high-frequency data can be extracted [258]. In addition to their use as gateways, edge computers were developed to analyze machine data directly, e.g., for closed-loop applications. Suppliers of edge computers and entire ecosystems for programming applications include Siemens, Beckhoff, and B&R

Closed-loop applications for machine tools: A sample monitoring system coupled with the digital twin of the machining process is shown in Fig. 17. MachPro software simulates the process states such as tool-workpiece engagement conditions, cutting force, torque, power, deflections, and chatter along the tool path [12].

Tool breakage, wear, contouring errors, and chatter occurrences are detected. The process force is adaptively kept at the desired levels by manipulating the feed. The occurrence of chatter could be avoided by controlling the spindle speed [16,47,213]. The monitoring algorithms used simulated sensory data to increase the robustness of the adaptive control and tool condition monitoring functions [160]. Schörghofer et al. [224] developed a closed-loop control for milling. Acceleration signals of a sensory tool holder were used to establish feed and cutting speed in-process adaption. Fig. 18 shows the different options to apply new set points for feed rate and spindle speed based on a Siemens 840D CNC control system.

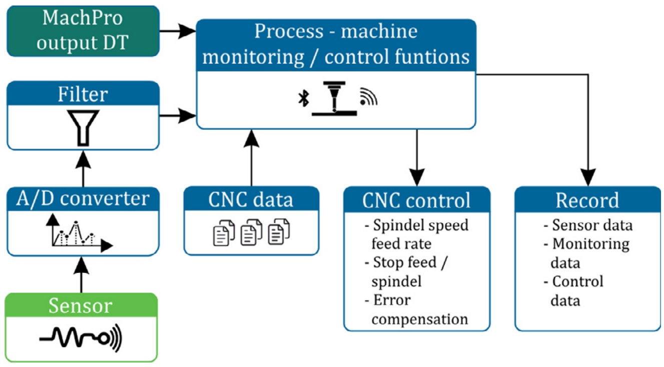

Fig. 17. IntelCut - Intelligent monitoring system architecture (Manufacturing Automation Laboratory – University of British Columbia).

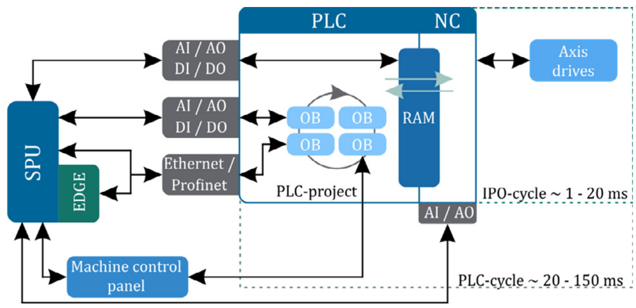

Fig. 18. Example of interfaces for closed-loop control, based on [224].

6. Sensor-integrated tooling systems

The sensor integration in the tooling systems aim to enable the measurement of physical process values by improved signal-to-noise ratio (SNR) in order to make the sensor systems as robust as possible against disturbances. Specific sensor integration solutions were elaborated with regard to the requirements of various process technologies (turning, milling, drilling, grinding, etc.). The different types of tools possess different boundary conditions for sensor integration and require specific approaches to gather the relevant signals by on-line or off-line data processing, and by real-time or non-real-time application.

6.1. Process metrology and monitoring

The sensor integration for process monitoring is discussed for stationary (e.g., turning) and rotating (e.g., drilling, reaming, tapping, milling, grinding) tools. Integration examples include the tool, the holder, or the spindle rotor and housing.

Turning: Some fundamental approaches for sensor integration in tools with defined cutting edges can be identified in turning which can be adapted to rotating tools like in milling and drilling. Sensors for measuring process forces, vibration, and temperatures are integrated directly underneath the cutting insert, in the tool shaft, or holder. The forces and vibrations can also be measured at a certain distance away from the cutting edge and the rake or flank face. Sensitive measurement of process temperatures requires to place the sensors as close to the chip formation zone as possible. For each type of sensor, particularly in temperature measurement, the influence of the heat transmission path from the source to the sensor's location has to be compensated. In force and vibration measurement, this applies to the dynamic characteristics (i.e., the transfer function) of the transmission path. Comparably to temperature measurement, most sensor integrations aim for positioning of the sensor as close to the cutting process as possible. A standard method for measuring process forces or low-frequency vibrations in turning operations is to use piezo-based dynamometers, which carry the tool holder. Grabec et al. [109] presented an approach for chatter detection that interpreted the normalized coarse-grained entropy rate of the cutting force signal obtained by a dynamometer. Similarly, Dimla and Lister [71] used a piezo-based dynamometer and a triaxial piezo accelerometer for observing the tool wear. The cutting forces and vibration signature in the time and frequency domains showed a good correlation with the wear status and progress. In [19], the signals of a piezoelectric accelerometer placed at the tool holder are processed by a decision tree and random forest learning algorithm to detect flank wear, tool breakage, and tool misalignment. The sampling rate was 25 kHz. The algorithm could classify the different tool errors with an accuracy of 95%. The use of accelerometer data for monitoring the workpiece's surface roughness was described in [101]. The sensor signals were processed by singular spectrum analysis. The surface roughness was estimated with 90% reliability. Fig. 19 shows a very compact and highly sensitive piezoelectric dynamometer setup for micro-cutting, as it is described in [53]. The tool holder that carried the diamond cutting insert was linked to piezoelectric elements operating in the X- and Y-directions via hemispheres and in Z-direction via a flexure hinge.

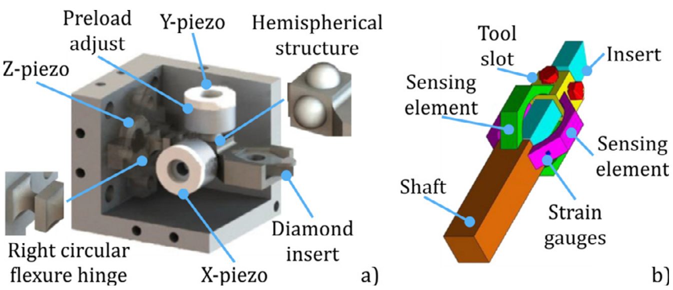

Fig. 19. Cutting force measurement, a) piezo based [53], b) strain gauge based [298].

The hemispherical structure decoupled the axial forces in different directions from each other. A force measurement resolution of 0.1 mN in X-, 0.05 mN in Y-, and 0.1 mN in the Z-direction was achieved at a sampling rate of 500 Hz. The three-axis fast tool servo equipped with a force measurement element was able to measure both static and dynamic forces up to 100 mN (X, Y) and 75 mN (Z), respectively. As an alternative to piezo-based dynamometers which suffer from signal drift and high costs, dynamometers based on strain gauge sensors were developed. In [291], octagonal rings are used as deformation elements with attached strain gauges. The specific arrangement of the rings leads to a minimal cross-sensitivity. The system was characterized by a maximum measurable force of 3.5 kN with a sensitivity of ± 5 N. In [298], an orthogonal arrangement of octagonal rings carrying semi-conductive strain gauges was realized to provide a dynamically stiff but sensitive force-measuring tool holder (Fig. 19). Compared to metal foil strain gauges, the semi-conductive type, fabricated by silicon-on-insulator piezo-resistive material, achieved a sensitivity improvement by factor 16. The system showed a natural frequency of 771 Hz. However, integrating deformation elements lowers the static and dynamic stiffness of a system, which can affect the chatter stability of the sensory tool. Temperature sensors should be as small as necessary to allow integration close to the cutting zone. Kus et al. [146] presented a sample integration of a K-type thermocouple with a measuring range of -195°C to 1,100°C underneath the cutting edge of a turning tool. The diameter of the thermocouple was 0.5 mm. The sensor could be located at a distance of 1 mm from the rake and flank face. The accuracy of the commercial sensor was specified at ±2.5°C or ±1%. In cutting experiments, the measured tool temperature values were compared to the temperature measurements at the tool-chip interface obtained from an infrared pyrometer. The tool temperature measurement values amounted to only about 13 – 20% of the temperatures of the tool-chip interface, depending on the process parameters. To close the gap between the two measurement approaches, an FE simulation of the heat distribution within the cutting insert was conducted. A combination of sensor data and simulation, also referred to as "soft sensor", can be used to correct the measurement data. In [123], thermocouples were integrated by blind holes with a diameter of 0.7 mm in the WC tool inserts at a distance of d = 0.15 mm to the cutting edge. This approach was combined with a "tool-work thermocouple setup" (see also [10]), in which the tool and the workpiece built a thermocouple system. The rake face-chip interface became the hot junction. Thus, the temperature at the tool–chip-contact and at different distances from the cutting edge could be investigated. The temperature distribution in the cutting zones can be measured directly by using thin film sensors located at the faces of the cutting insert. Basti et al. [27] explained the design of thin film Ni/NiCr thermocouples which were placed at the rake face of Al_2O_3 inserts by magnetron sputtering, insulated by an HfO_2 layer and covered by TiN, TiAlN or TiAlSiN protective layers. Photolithography and chemical etching formed the 0.5 µm thick structure of the thermocouples (Fig. 20). The sensory cutting inserts were tested and validated in cutting experiments. In [60], NiCr/NiSi thin film thermocouples with SiO_2 insulating and protecting layers were deposited at HSS substrates by a special magnetron sputtering technique. The sputtering of Alumel-Chromel thermocouples at WC-Co inserts using micro-machined masks was described in [136]. A 100 nm thick chromium layer was used as an adhesion promoter. The thermocouple structures were embedded in an Al_2O_3 dielectric coating to decrease stresses due to the substrate's and the coating's different thermal expansion coefficients. Finally, an AlTiN protection layer was added.

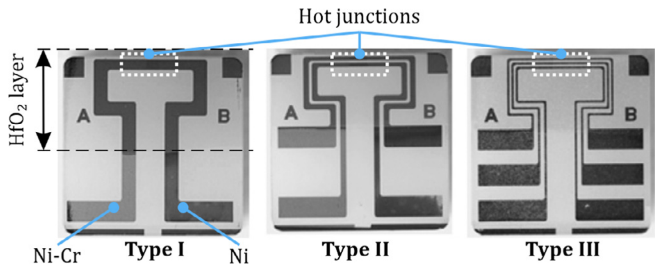

Fig. 20. Built-in thin film thermocouple sensors [27].

The temperature of the tool chip interface could be measured even in the interrupted cutting of AISI 12L14 steel with cutting speeds up to 200 m/min. In [155], thin film thermocouples were embedded in PCBN tools and tested in dry hard turning of AISI O2 tool steel hardened up to 62 HRC. An array of 10 hot junctions was placed within an area of less than 1 mm^2. Temperatures of up to 1,100°C at the rake face and 650°C at the flank face could be measured by the sensory system in experiments at cutting speeds from 250 m/min to 1,000 m/min. In [283] and [284], tungsten-5% rhenium and tungsten-26% rhenium build C-type thermocouples were used with a working temperature above 2,000°C. The sensor structures were created by diffusion bonding at PCBN inserts. In cutting tests, the aluminum alloy 6061 was machined. Furthermore, in [285], these sensors were applied in hard turning of AISI O2 steel with 58 – 64 HRC showing high linearity up to 1,300°C and fast response time. The deposition of NiCr/NiSi thin film thermocouples at PCBN by magnetron sputtering was described in [297]. Tillmann et al. [252] explained the creation of Ni/NiCr thermocouples deposited by an Arc-PVD process on Silicon Nitride inserts using a novel masking method. Grit blasting and plasma etching were investigated to improve the adhesion of the thin film sensor structures to the substrate. Integrated thin film thermocouples by using differently machined micro-grooves have been proposed [154,231]. Sugita et al. [244] used the WC-Co insert as one pole of a thermocouple with Cr as the other. The Cr-layer was separated from the insert by an Al_2O_3 insulating film. The two poles contacted each other only at the measuring point, i.e., the hot junction. The thermal capacity and thus the response time were reduced. In [209], thermo-resistive Cr thin film sensor structures were created using physical vapour deposition (PVD) at cemented carbide inserts with a distance of 200 µm to the cutting edge. Al_2O_3 layers were deposited underneath and above the sensor structure for insulation and wear protection. In cutting tests of AISI 4140, the temperature measuring capability was validated. Wang et al. [274] realized a miniaturized thermistor sensor by aerosol jet printing of a Nickel Oxide nanoparticle ink at tungsten carbide inserts with an Al_2O_3 insulation layer. Also, the conducting wires were produced by aerosol jet printing of silver nanoparticle ink. The NiO thin films had to be thermally calcined in a furnace. Micro-structured thin film sensors can also be used to measure tool wear directly. In 1976, Micheletti et al. [175] reported an approach, additionally published in 1973 by Uehara [261], in which thin film resistors were located at the flank face of the tool. This setup enabled the measurement of flank wear by a change of the electric resistance due to the removal of the conductive structure. The resistors were produced either by printing graphite ink or by vacuum evaporation of Cr using a mask. A thin layer of heat-resisting paint was applied for insulation. Thin film sensors are used to measure the process forces by piezoelectric elements that are mounted between the cutting insert and the interface at the tool holder [54]. Due to thermal influences affecting the measuring results, the approach was combined with strain-sensitive surface acoustic wave sensors at the tool holder. Cutting forces were measured up to 175 N, comparable to a Kistler dynamometer. Sensory turning tools are characterized by a quasi-stationary, non-rotating tool body. There is no need for a transmission of energy and sensor data via any interface between fast-moving and stationary components. Similar boundary conditions apply to boring with a non-rotating tool. Wired accelerometers were attached to boring bars to detect chatter vibrations in [219] and [212].

Drilling, Reaming, Tapping, Milling: A transmission of energy and sensor signals is necessary for rotating sensor systems. Depending on the rotational speed, different solutions can be implemented. This allows for sensor integration in tools rotating at high speeds. Sensor integration often involves the spindle system of a machine. The use of piezoelectric rings at the front bearing and flange of a motor spindle for force sensing in drilling was described in [46]. The sensor signals were sampled at 2 kHz. Besides process-related effects, also characteristics of the spindle could be identified. In [29] a piezoresistive thin film sensor system with a thickness of 7 µm was deposited directly at the front surface of a spindle shaft to monitor the clamping force and imbalance of a tool in woodworking. The piezoresistive hydrogenated carbon layer constituted a further development of diamond-like carbon (DLC) coatings to provide high wear resistance. Capacitive sensors measuring the displacements between the spindle housing and the rotating shaft were introduced in [11]. The measurement of displacements caused by process loads at the tool was utilized as an indirect force measuring system. Using a Kalman filter, the bandwidth could be increased up to 1 kHz. A similar approach was applied by Brecher et al. [37]. The measured process forces were compared with simulation results to achieve an online monitoring system. In [20], the prediction of the workpiece topography affected by tool vibrations and measured by displacement sensors was described. In [182], the complete milling spindle was carried by a piezo-electric structure. Process forces could be measured, and deflections of thin-walled workpieces were observed. Dini and Tognazzi [72] presented a sensory tool holder which was able to measure the torque in milling. A wireless torque measuring system (Montronix) was mounted at a modified standard tool holder. This device provided a resolution of 0.1 Nm. Due to the modification, the torsional stiffness of the tool holder was reduced. In [216], a strain-gauge-based sensory tool holder for milling and drilling was presented. A special force transducer in the form of a rectangular parallel-piped housing of the tool holder was equipped with 24 strain gauges within Wheatstone bridges. The layout considers process forces ranging from 2 kN to 3 kN and spindle speeds of up to 5,000 rpm. In [170], a sensory tool holder was analyzed to monitor tapping and end milling processes. Four piezo acceleration sensors were integrated with the tool holder and allowed for multi-axis vibration measurements. Stick-slip effects in tapping and chatter in milling could be observed. Öztürk et al. [201] introduced a sensory tool holder system for identifying uncertainties in tapping. Two uni-axial capacitive MEMS accelerometers with a bandwidth of up to 11 kHz and a measuring range of ± 100 g were placed on a printed circuit board (PCB) in a casing that was mounted directly to the tapping tool by adhesive bonding. A spring element with attached strain gauges was designed to monitor the axial compensation inside the tapping tool holder. In [216], an accelerometer and a type-K thermocouple at the interface between the tool holder and a cutting insert were additionally integrated to establish a multi-sensor system for comprehensive process condition monitoring. Instead of strain gauges, Xie et al. [289] proposed the use of capacitive sensors and a deformable structure for measuring process forces in three directions as well as torque inside a tool holder. With a prototypic system, a high sensitivity could be achieved. Nevertheless, the sensitivity depended on the manufacturing accuracy of the sensory structure. The overall dimensions of the tool holder required considerable space, which might reduce the accessibility of workpiece geometries and preclude automatic tool change. An integrated wireless vibration sensing tool holder for monitoring of milling processes is presented in [288]. A single-axis MEMS capacitive accelerometer was placed at the rotational axis using a holding bracket. Wireless data acquisition electronics required an increased space of the complete integrated system. Sensitive vibration signals could be obtained, which allowed tool wear monitoring. A much more compact solution of an acceleration sensor integrated tool holder was deployed by Bleicher et al. in [34,214]. Fig. 21a shows a design variant which was currently commercialized by the company Schunk.

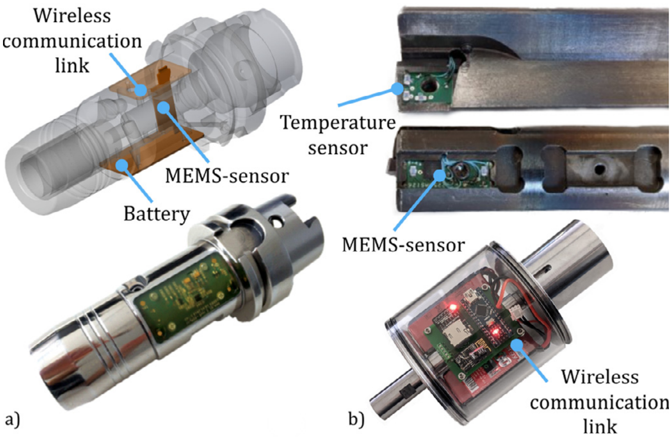

Fig. 21. MEMS-sensors integrated in tool holders, a) sensory tool holder, b) sensor-integrated deep hole drilling tool.

Because an exact positioning of the MEMS acceleration sensor at the rotational axis was hardly possible, a model-based signal pre-processing was necessary. In [292], a tool holder containing two uni-axial piezoelectric acceleration sensors was presented. The aim was to measure vibrations in tangential (rotational) and radial direction with a 1 kHz bandwidth. The sensory system allowed chatter detection and avoidance by changing the spindle speed. A tri-axial vibration sensing tool holder was introduced in [300]. A piezoelectric accelerometer was combined with tailored micro-electronics. In [235], Spiewak introduced a similar system and described a calculation method to convert acceleration measurements into spindle vibrations. Besides the mentioned designs, also the tool shaft or tool body enables sensitive sensor integration. A strain gauge bridge was attached directly to the shaft of a milling tool in [247]. In [141] and [197], an integrated laser system was introduced that measured the deflection of a rotating boring bar to allow an active adjustment of the cutting insert position. The application of a screen-printed PVDF polymer film sensor laminated between a polyester substrate at a boring bar was reported in [204]. Vibration signals could be derived from the measured strain. In [173], FBGs were attached to a carbon fiber reinforced composite drill tube for single tube system (STS) deep hole drilling to measure torsional tool vibrations. The sensors were sampled sequentially at 19.23 kHz during 1 s period. Compared to strain gauges [174], the FBGs sensors showed a drift, which was explained by the influence of the adhesive bonding. In [39], a reaming tool was presented that measured straightness deviations by strain gauges attached to the tool shaft (cf. Fig. 22). The layout of the Wheatstone full bridges provided a decoupling of torsional stresses and normal forces with robustness against temperature influences. A battery energized the sensor elements and a telemetric system realized the signal transmission. After low-pass filtering, amplification, conditioning, and another low-pass filtering of the raw signals, an AD conversion was implemented at a sampling rate of 83.3 kHz (three channels) with 16 bit resolution. The conversion required 2.2 µs and the transfer to a micro-controller took additional 4 µs which is a negligible delay. Data transfer to a stationary data acquisition (DAQ) system used the ZigBee standard. High sensitivity and linearity of the sensory system were achieved.

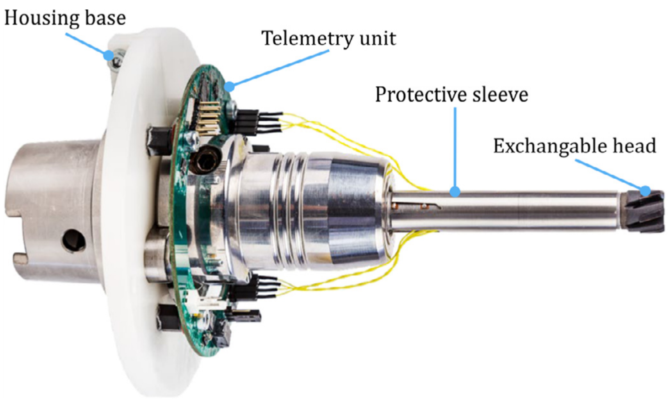

Fig. 22. Measuring the bore straightness during reaming with sensory tools [39].

There are also approaches available for sensor integration at the tip of rotating tools. In an 18 mm deep hole drilling tool eight Pt1000 thermal sensors were integrated underneath the cutting insert and the guide pads including a capacitive accelerometer close to the tool tip [281] as shown in Fig. 21b. Accelerations up to ±40 g could be measured. The sampling frequency was 8 kHz. A specific telemetric system was designed. In addition, the analyses of process temperatures and feed forces under various process conditions were presented. Due to the distance of the temperature sensors from the cutting edge and guide pad surfaces, soft sensor simulations were necessary to scale the measured temperatures. Some acceleration sensing tool systems with additional features like temperature sensing are commercially available, e.g., Multi Intelligence by Yamamoto et al. [292]. Totis et al. [257] presented a milling tool dynamometer in

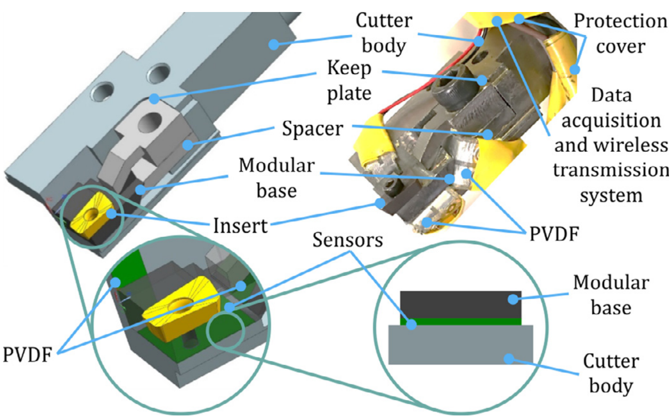

Fig. 23. A wireless instrumented milling cutter system with embedded PVDF sensors [164].

which triaxial cutting force signals were gathered at each cutting insert. The four inserts were carried by modular cartridges, which were mounted at the tool body via piezo-electric sensors. A bandwidth of 1.5 kHz could be achieved. As an alternative to bulky piezo-electric force sensors, [164] introduced a milling cutter with thin film PVDF sensors at each cutting insert (cf. Fig. 23). The sensors were placed under the insert seats and worked at an operating frequency of up to 10 MHz. Crosstalk was compensated by decoupling the signals. Drossel at al. [77] chose piezoceramic thick film sensors in the clamping of cutting inserts of a milling cutter. The modular system involved sensor plates between the tool body and the inserts at which the sensory PZT (Pb (Zr, Ti)O_3) multi-layer system was deposited. Ting et al. [253] applied multiaxial single-layer PVDF thin film sensors directly at the interface between the milling tool shaft and the tool holder. To calculate the cutting forces based on the signals of the distributed sensor electrodes, a model computing the bending and torsional moments was developed.

Möhring et al. [184] integrated a MEMS acceleration sensor at the tool-tip of a 120 mm long 12 mm ball nose milling tool (Fig. 24). The uniaxial sensor provided a sampling rate of 16.4 kHz. A three-channel transmission system with 80 kHz sampling rate communicated the sensor data from the rotating tool. Since the sensor was positioned directly next to the cutting insert at the tool-tip, tool vibrations could be measured. Monitoring the resulting workpiece roughness during milling operation was possible [180,181]. Besides forces and accelerations, temperatures in the cutting zones are essential in process and tool condition monitoring. In [150], K-type thermocouples were integrated into uncoated carbide tools with a diameter of 10 mm to measure process temperatures in the drilling of Ti6Al4V. A wireless transmission system at the tool holder was used to communicate the sensor data to the DAQ system via an RF antenna. An acquisition frequency of 1 kHz, an accuracy of 1°C and a measurement delay of 150 µs were achieved. Lazoglu et al. [149] developed a tool holder to measure the temperature in a drilling process. The telemetry was integrated into a dynamometer so that the forces and moments were recorded in addition to the temperature. The temperatures could be measured directly at the cutting edge via two thermocouples guided through the cooling channels. In [49], a K-type thermocouple was integrated into a milling tool insert to measure temperatures close to the cutting zones. In this application, a small hole was drilled into one of the cutting inserts. A temperature resolution of 0.68°C was achieved. The system allowed to distinguish temperatures depending on the cutting speeds. A NiCr/NiSi thin film thermocouple integrated into a milling tool cutting insert was presented in [59]. SiO_2 films were used as insulation and protection. Temperature curves were generated for different cutting depths. The integration of a K-type thermocouple into a monolithic solid carbide milling cutter with a diameter of 8 mm was presented in [135].

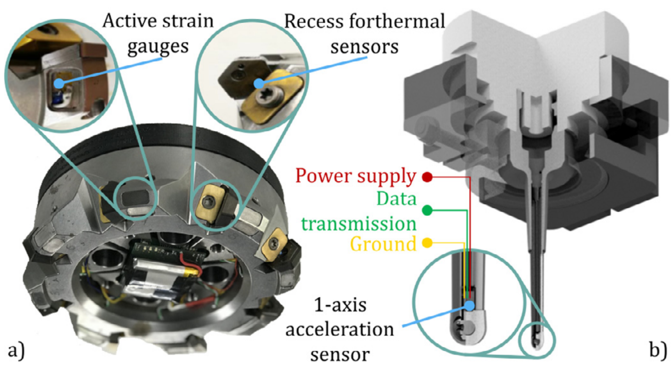

Fig. 24. Intelligent tools for predictive process control [184,185].

The diameter of the thermocouple was only 0.2 mm, and the nominally rated response was given at 20 ms. The sensor was placed 0.5 mm away from the cutting edge. In [136], thin film thermocouples were directly deposited at the surface of the cutting insert of a milling tool. Thus, a distance to the rake face and the cutting edge of only 1.3

µm and 20 µm could be realized. The data transmission was based on slip rings. An alternative principle was introduced in [217]. A ceramic dielectric ring resonator mounted on a tool was used. Using radio-frequency backscattering, the temperature was obtained from its resonance frequencies. This allowed reading the temperature-related values at a larger distance and with a closed machine door. Furthermore, systems involving multiple different sensor technologies for multi-physical measurements were elaborated. In [185], a multi-sensory milling head and its use for process monitoring were presented (cf. Fig. 24). The tool body was equipped with strain gauges at each cutting insert for force measurement. K-type thermocouples allowed temperature measurement close to the cutting zone. Moreover, a 3-axis accelerometer was integrated for vibration measurement.

Grinding: Sensory tooling systems were investigated for grinding in [95,134]. Sensor integration into grinding tools must consider the specific characteristics and conditions of the grinding processes, such as intensive coolant supply, high contact frequencies of the grains, and high bandwidth of excitations. On the other hand, the characteristic structure of grinding tools makes it possible to implement specialized types and designs of sensors. Varghese et al. [266] introduced a sensor-integrated grinding wheel with piezoceramic sensors integrated into an aluminum core that carries abrasive diamond segments. The normal forces acting on the grinding wheel were measured during rotation. In addition, acoustic emission signals were obtained by a sensor near the wheel's bore. The truing process could be monitored to achieve a minimum tool run-out. The measured grinding forces were comparable to reference dynamometer readings. Brinksmeier et al. [41] introduced a thermocouple directly integrated into the grinding layer that allowed continuous contact with, e.g., the workpiece even during progressing tool wear (Fig. 25). The connecting point of the thermocouple was established during grinding since the upper margin of one of the two sensor elements was smeared across the insulation under process contact conditions.

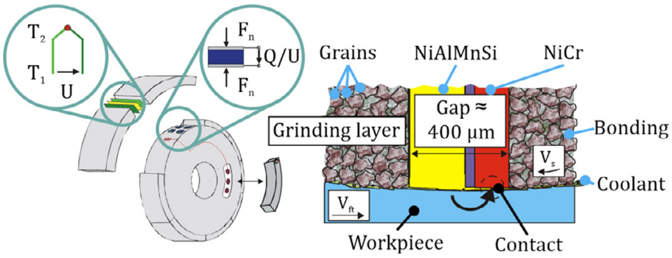

Fig. 25. Wheel-based process monitoring system in grinding [41].

6.2. Process control

Measuring process values by sensor-integrated tooling systems enables adaptive process control applications. The feed drives and the main spindle motors can be utilized to adapt process parameters like feed velocity and cutting speed. In this case, the process controller derives modified set values by computing the process data from the sensory tooling systems according to a given process control law and communicates these values to the CNC. Commercial systems are provided, e.g., by Marposs, Ceratizit, and others. On the other hand, actuators can be integrated into the tooling systems in addition to the sensors. Closely coupled sensor-actuator systems allow for a high process control bandwidth depending on the dynamic properties of the actuators and the controller performance. The integrated actuators provide additional active degrees of freedom which can be used besides the machine tool's feed axes to influence the machining process. However, integrated actuators require an energy supply to satisfy the significantly higher energy demand compared to the sensor applications. In [33,34], the use of a sensory tool holder from Fig. 21a with a machine learning approach was described. The aim was to avoid chatter in milling by adaptively controlling the feed rate and rotational speed. The communication with an exemplary Heidenhain iTNC 530 controller used ethernet transmission towards a National Instruments DAQ. The Heidenhain DNC software interface with the RemoTools software development kit comprised COM components and Active X control. Similar control architectures were realized with B&R [223] and Siemens [224] controllers (Fig. 26). In [171], the process control was extended by a material removal simulation and a modification of the NC-code.

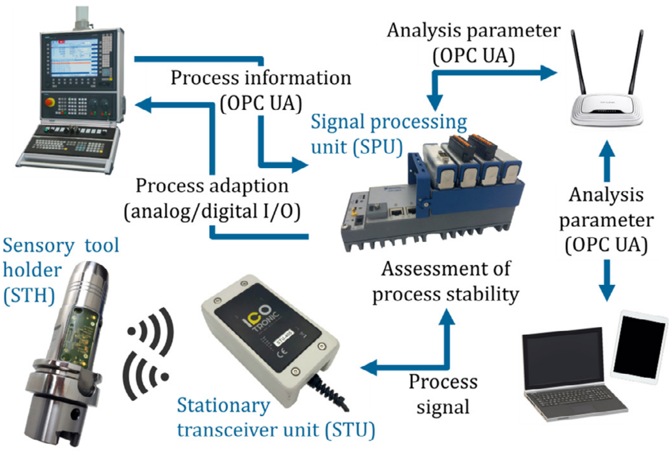

Fig. 26. Communication structure of the in-process control system [224].

Möhring et al. [94] investigated a process control based on the sensory integrated ball nose tool as shown in Fig. 24. The tool recognized the early onset of chatter. By coupling with the Siemens Sinumerik control of the machine tool, an in-process adaptation of feed rate and spindle speed was implemented. In the course of the entire useable tool life, wear-dependent stability limits could be identified (cf. Fig. 27a and 27c). The process could be adapted to avoid instability, which is depicted in Fig. 27b and 27d. For instance, in [73,153,229], examples of chatter suppression by closely coupled sensor-actuator systems were introduced. Critical tool vibrations were recognized, e.g., by strain gauges attached to the tool shaft [73,229] or displacement sensors looking at the tool holder in front of the spindle bearings [153]. Using additional actuators, counteracting forces were applied to the tooling system to diminish chatter vibrations without any human interaction with the machine controller.

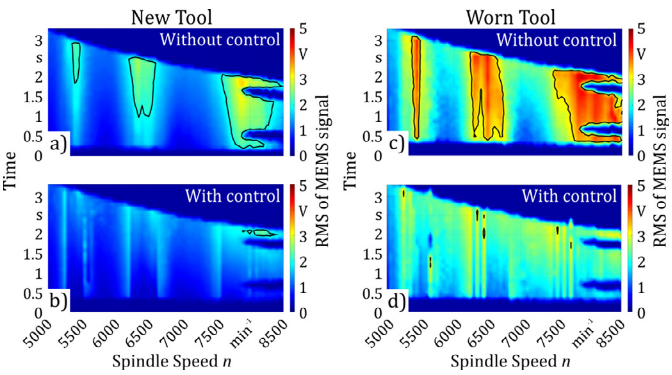

Fig. 27. Results of the machining process control [94].

Based on soft sensors, Stampfer et al. [236] showed a closed-loop control approach for the measurement of surface layer states such as grain size, hardness, and residual stresses. An observer model used sensor signals from thin-film temperature sensors at the tool insert. As early as the mid-1990s, there were initial developments in sensor- and actuator-integrated tools, in which closed-loop control was established. Choudhury et al. [56] developed a turning tool with integrated actuators. The vibrations between the tool and the workpiece are detected online with bifurcated optical fibers. If instability was detected, an exciter generated opposite forces to stabilize the vibration. A summary of monitoring and closed-loop concepts was provided by Cao et al. [50] with a focus on concepts located in the spindle.

7. Actuator integrated tooling systems

A large number of different tooling systems are deployed in research environments and industry [75]. Actuated tooling systems are used for both, cutting processes with defined and undefined cutting edges [32,52,169]. Depending on the field of application, they can be divided into applications for process assistance (Section 7.1), process adaptation (Section 7.2), and systems with additional actuated axes (Section 7.3). In process assistance, the function of the actuator supports the primary process of material cutting to improve the process conditions or to take influence on the material behavior, the tool engagement, and tool life [38,52]. In process adaption, the actuator is used as an active element to improve process stability and component quality [13,105]. Tooling systems with additional axes are usually designed for special applications in the machining of parts with complex shapes or other special requirements, e.g., the machining of undercuts. The range of realized systems extends from simple systems, in which the actuator superimposes a movement of the tool tip without feedback control [130], to highly sophisticated systems with a high degree of integration and a sensor-based closed-loop control [67,68,162].

In the design of tooling systems with actuator integration, the selection of the actuator principle is strongly dependent on the frequency and stroke or amplitude requirements of the system [35]. While mechanical and hydraulic actuators typically realize a high amplitude at low frequencies [172], the application range of e.g. piezo-electric actuators extends into the ultrasonic range [93,262]. Fig. 28 shows the typical range of the respective actuator principles for tooling systems according to [35].

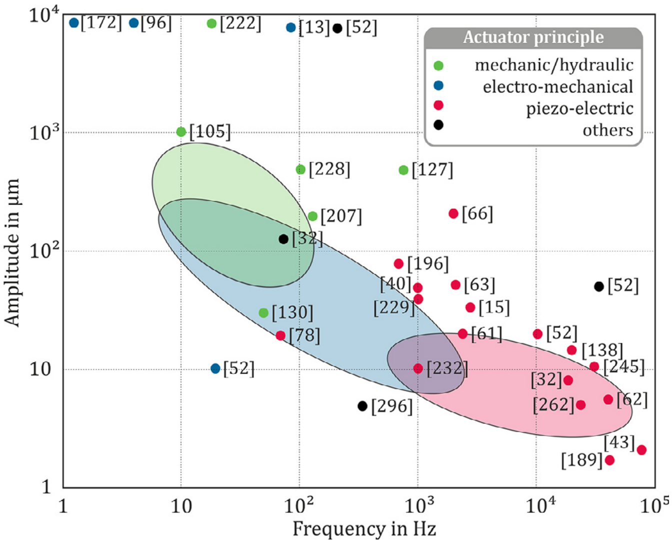

Fig. 28. Range of amplitude and frequency of actuator systems for different actuator principles, based on [35].

Each point in the figure represents a system referenced in this paper. The term “other actuator principles” includes, for example, systems based on magnetorheological fluids, magnetic actuators, or systems based on shape memory alloys. The positioning of the actuators varies from direct integration into the tool, actuators in the tool holder or the spindle, to systems that influence the behavior of the tooling system via the spindle rotor [1] like bearings or additional structures (cf. Fig. 3).

7.1. Process assistance

Tooling systems with integrated actuators are used for a wide range of machining applications. In addition to tooling systems for drilling, milling or turning [67,207,262], process assistance is also realized in superfinishing operations such as grinding or honing [74,265]. The assistance of the processes by actuated tooling systems aims to reduce the tool load, improve the tool life, and increase the process efficiency. When the actual cutting movement is superimposed by the actuator's motion, various mechanisms can have a positive effect on the machining process. In the machining of brittle materials [32], the formation of micro-cracks in front of the cutting edge and thus the weakening of the material leads to lower process forces. The relative motion between the tool tip and the workpiece comes along with improvements in the flushing of lubricant at the contact zone [32] and thus with an enhenced cooling effect of the cutting edge [286]. Compared to the continuous engagement of the cutting edge, the application of the superimposed alternating motion with larger amplitudes results in an intermitted cut and an improved breakage of long chips [228]. These effects are summarized in Fig. 29.

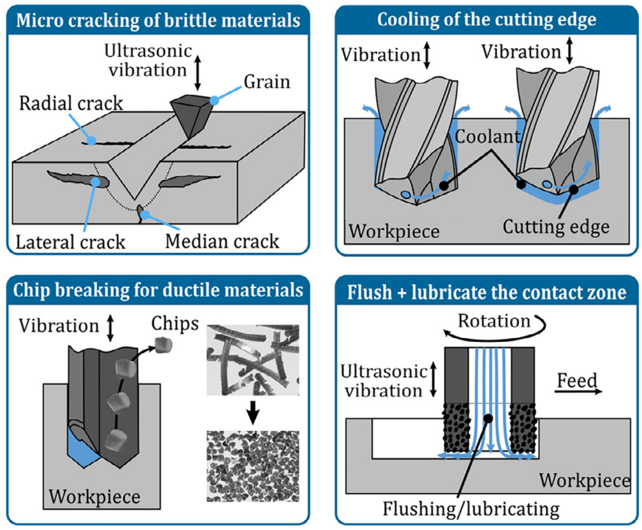

Fig. 29. Benefits and mechanisms of process assistance with actuated tooling systems.

Most tooling systems with integrated actuators that are used to assist cutting processes superimpose a vibration on the cutting motion. A distinction can be made between low-frequency and ultrasonic vibration-assisted machining systems, either synchronous or non-synchronous to the rotational speed of the tool. In addition to the frequency and amplitude, the systems can also be classified according to their available degrees of freedom. While simple systems for drilling or turning usually generate a one-dimensional vibration [38,62], some systems can realize micro-movements in multiple planes (axial linear, rotational, and tilting) [66,99,144]. Depending on the design of the tooling system and the corresponding control, the superimposed vibration can be realized as force- or stroke-controlled [40]. The positive influence of vibration support on various machining processes has been proven in a large number of investigations [52,144,299]. Characterized by relatively low amplitudes and high frequency, a large part of the tooling systems is based on the use of piezoelectric actuators. In the field of stationary tool holders for turning, Moriwaki et al. [189] developed a system for one-dimensional superimposition of the cutting movement in the axial direction of the tool. The vibration support for turning with diamond tools reduced tool wear when machining stainless steel and enabled ultra-precision machining with a surface roughness in the nanometer range. Bulla et al. [43] used a similar system when turning hardened steel with diamond tools and were able to achieve optical surface qualities by increasing the vibration frequency to 80 kHz. Khajehzadeh et al. [138] realized a system based on the use of piezoelectric actuators for two-dimensional elliptical vibration assistance of the turning process in the cutting and feed direction while turning hardened steel.

In the field of rotating tooling systems, process assistance also focuses on the superimposition of the cutting motion realized by the use of piezoelectric actuators. In contrast to stationary systems, the signal and energy transmission for rotating tools is significantly more complex. Bleicher et al. [40] developed a piezoelectric tool holder with an axial amplitude of up to 50 µm and a frequency of up to 1 kHz for low-frequency assisted grinding. For the energy supply of the piezo stacks, a contactless energy transfer system based on inductive coils was developed. In [99], Gao et al. presented a three-

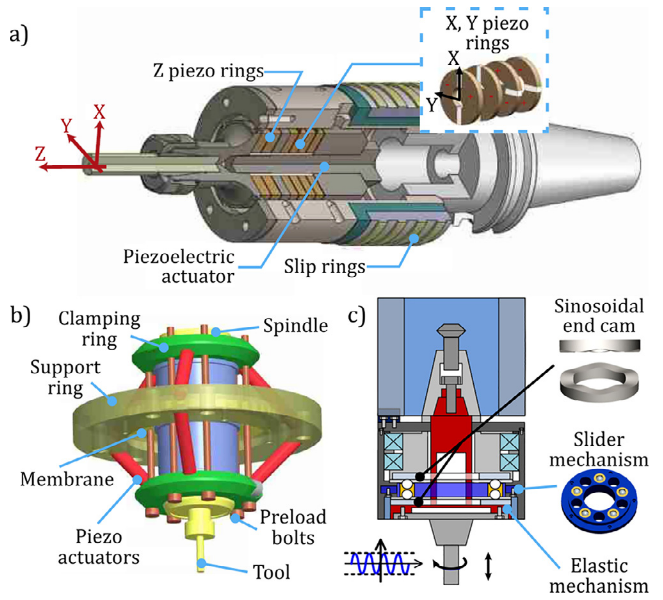

Fig. 30. Prototype actuator tooling systems: a) piezoelectric tool holder for ultrasonic vibration [99], b) adaptronic spindle system with piezoelectric actuators [66,68], c) mechanically actuated tool holder [130].

degrees-of-freedom tool holder for ultrasonic-assisted drilling and milling. In addition to the superimposition of an axial motion, a deflection of the tool in X- and Y-direction was enabled by this design (cf. Fig. 30a).

The deflection effect was based on stacked piezo rings with an energy supply by slip rings. Sensorless closed-loop control was possible via the ratio of driving currents and supply voltages. The main fields of application of these and similarly designed tooling systems are the machining of CFRP/Ti6Al4V stacks to avoid defects such as delamination [127] or the reduction of process forces when grinding brittle-hard materials like ceramics [265]. Wang et al. [277] developed a core drilling tool that allowed deformation of the tool in the torsional direction based on the feed force and thus longitudinal-torsional vibration for drilling processes. In addition to systems that provide pure process assistance through vibrations, tooling systems have been developed that can also realize a process adaptation with integrated piezo actuators. Denkena et al. [68] developed an adaptronic spindle system in which piezo actuators enabled both, vibration-assisted machining and a process adaptation with a controlled compensation of tool displacement. The special arrangement of the piezo actuators allowed not only for the movement of the tool center point in all three spatial directions but also for the tilting of the entire spindle system (cf. Fig. 30b). By the dynamic positioning of the spindle, it was possible to mitigate the occurrence of unwanted vibrations and unstable process conditions due to the regenerative effect [66]. Dröder et al. [74] developed a piezo-hydraulic actuator system to assist the honing process. To realise a force-controlled honing process, the system used the high-velocity fluid pressurized by a piezo actuator to press the honing stones against the cylinder wall. Fast tool servo systems are an extension of simple piezo actuators, which enable extremely fast and precise positioning of the tool or the cutting edge through appropriate control. In this regard, Denkena et al. [70] investigated the use of tooling systems with integrated fast tool servos for the generation of surface structures and for influencing the properties of the workpiece's surface-near zone during milling and hammer peening. With an extension of the system, coded markings could be generated on the components during face milling [296]. Jiao et al. [130] presented a mechanically actuated tool holder for low-frequency vibration-assisted drilling to generate chip breakage in machining difficult-to-cut materials. The system used a slider mechanism between two sinusoidal end cams to generate an axial movement of the drilling tool with a fixed amplitude and frequency depending on the design of the end cams (cf. Fig. 30c).

Most of the systems developed for process assistance are prototypes out of a laboratory environment. Industrial implementation is usually hindered by the high costs of the individual components, and limited to specific applications of a small number of suitable machine tools. When retrofitting the machine tool systems, the integration of the actuator control is usually complex due to the typically closed architecture of the CNC controls. A commercial implementation of a tool holder with piezoelectric vibration support for drilling and milling was presented in [76]. The control and energy supply of the “PermaVib” system are independent of the energy supply and control of the machine tool. Ultrasonic systems for high-precision diamond turning with optical quality were developed by Precitech and SON-X [43]. In addition to a piezoelectric spindle, Mitis in [207] (cf. Fig. 31c) deployed tool holders with mechanical actuators based on sinusoidal bearing races with a mechanism to vary the amplitude at fixed frequencies. A mechanical axial pulsator that can be used to optimize chip formation during deep hole drilling of ductile materials was described in [228]. In addition to various systems offered as tool holder retrofit setups, fully integrated systems are also available in dedicated machining centers mainly for vibration-assisted machining. Uhlmann and Feucht [93,262] carried out their investigations in milling and grinding on five-axis ultrasonic machine tools of the type Ultrasonic 260 Composites from DMG MORI.

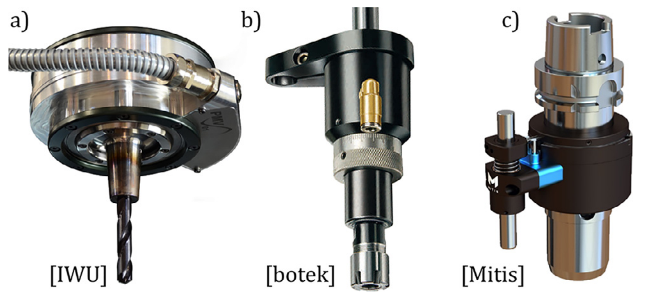

Fig. 31. Industrial solutions for process assistance: a) PermaVib piezoelectric vibration tool holder, b) Botek mechanical axial pulsator, c) Mitis mechanical vibration tool holder.

7.2. Process adaption

The actuators used for process adaptation are usually not able to support the process directly, but they are used against unwanted effects and problems such as vibrations and displacements during machining. However, this can be achieved by compensation or a change of the mechanical properties, e.g., damping of the tool spindle system [13,15]. Numerous examples of adaptations can be found for internal turning operations with boring bars and milling operations. Adaptations are also found in hard turning, fine boring, single-lip deep hole drilling, and single tube system (STS) drilling.

Boring bars are usually slender structures with long overhangs. Thus, they are highly susceptible to chatter vibrations [13,88,203,219]. Tuned mass dampers (TMD) are built into boring bars to improve damping characteristics and reduce chatter. In 1969, Holmen developed one of the first TMD boring bars. The TMD was adjusted by a threaded knob at the end of the boring bar [120]. Since then, several boring bars with TMD were developed with the possibility to adjust the TDM while machining. Abele et al. [4] described a modular fine boring tool with an active TMD and integrated power and control electronics for adjustments. Altintas et al. [13] developed a power screw-driven TMD to automatically tune in the natural frequency with the help of an electro-magnetic impulse force exciter. The tuned TMD can then be used on different boring bars. Fig. 32 shows the developed solution by Holmen (top) and the more sophisticated system by Abele (bottom).

Instead of a TMD, Saleh et al. [219] used a magnetorheological (MR) fluid damper to control chatter in the boring process. A commercial tooling system for the TDM process adaptation is the Sandvik Coromant Silent Tools line. This tooling system consists of a pretuned TMD which is integrated into turning, milling, and boring tooling systems. Ingersoll Cutting Tools (IMC Group) also provides a modular TMD boring and milling system called T-Absorber. These commercial systems, however, are passive systems that cannot be

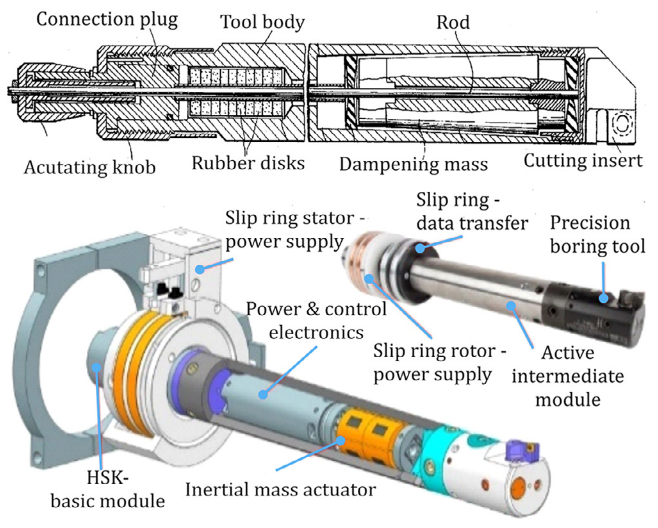

Fig. 32. Top: System developed by Holmenin 1969 [120] Bottom: Active TMD-boring bar developed by Abele [4].

tuned while machining. Another way to reduce chatter is to overlay additional vibrations while using a boring bar. Fallah et al. [88] developed an inverse chatter control with an electromagnetic shaker connected to the boring bar. The chatter vibrations were measured and phase was shifted to cancel vibrations via the shaker activation. Pratt et al. [212] used two magnetostrictive Terfenol-D actuators in two directions and piezoelectric sensors to actively mitigate chatter while machining. Harms et al. [67] developed a tool holder with integrated multilayer piezoelectric actuators to compensate for the vibrations in turning. Lu et al. [162] described an active contactless damping system for boring bars based on a magnetic actuator. In contrast to magnetostrictive actuators, e.g., piezo or Terfenol-D, the magnetic actuators reveal the advantage of linear behavior. Wenshuo et al. [166] integrated a TMD as a passive damping system into the shaft of a long milling tool. Due to the rotation of the milling tool, an in-process adjustment of the TMD was not possible.

Contactless magnetic or electromagnetic systems consist of a static and a rotating element. Due to a magnetic field, forces can be applied without contacting the rotating part. These elements are either positioned at the spindle nose, inside the spindle housing, or in bearings as shown in Fig. 33. Active magnetic bearings (AMB) are capable of acting as contactless sensors or actuators.

Abele et al. [5] added AMB into the spindle, which was used to determine the frequency response function (FRF) of the spindle-tool system. Furthermore, the AMBs were used to actively damp the rotor system in milling. Emmrich et al. [87,140] and Königsberg et al. [87,140] developed a spindle-integrated actuator based on a permanent magnet synchronous machine to reduce chatter. The deflections were measured with eddy current sensors. Wan et al. [272] embedded eddy current sensors and an electromagnetic actuator in the spindle nose to mitigate the vibration of the rotating tool.

Möhring et al. [186] developed a milling tool holder for large shell mills with a passive friction damper and an active magnetorheological fluid damper to achieve higher material removal rates and improved surface qualities. Piezoelectric actuators are also used to damp chatter vibration or to compensate for the milling tool deflection. Wang et al. [275] and Sun et al. [245] used piezoelectric actuators to reduce chatter. Denkena et al. [69] deployed piezoelectric actuators for online compensation of the tool deflection using the spindle nose as a fluxure joint. Altintas et al. [15] developed a system for the compensation of tool deflections in hard turning with piezoelectric actuators. The tool position was controlled within $\pm$ 10 nm. Gerken et al. [105] developed an in-process compensation for the straightness deviation of the STS deep hole drilling process. The use of an ultrasonic measuring system, the compensation unit attached to a modified boring bar and two servo motors are used to reduce the straightness deviation by 51%. Weinert et al. [281] presented a tool holder with an integrated MRF damper to reduce chatter in single-lip deep-hole drilling, which is illustrated in Fig. 34.

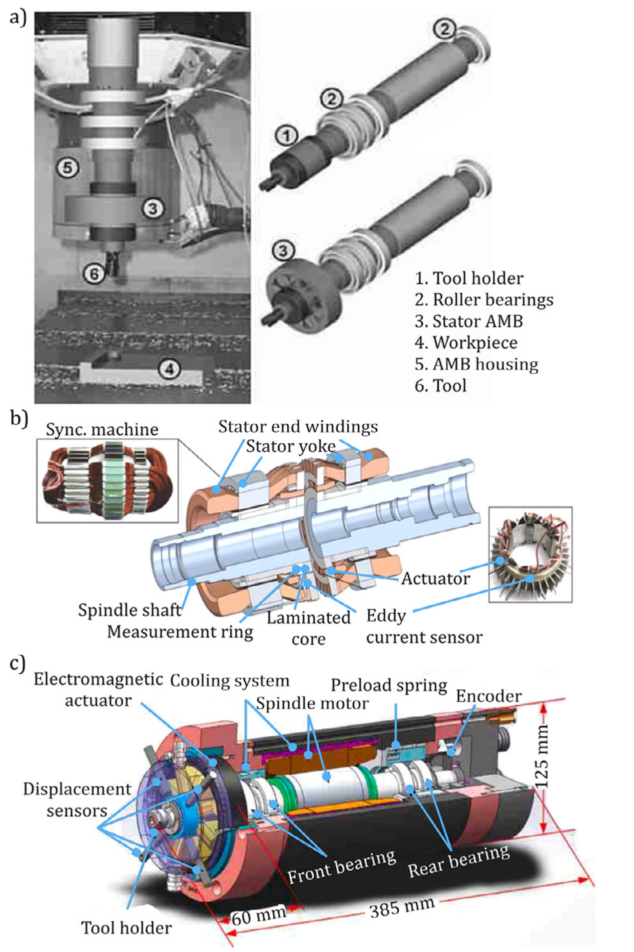

Fig. 33. a) AMB integrated into a milling spindle [5], b) permanent magnet synchronous machine [87,140], c) electromagnetic actuator at the spindle nose [272].

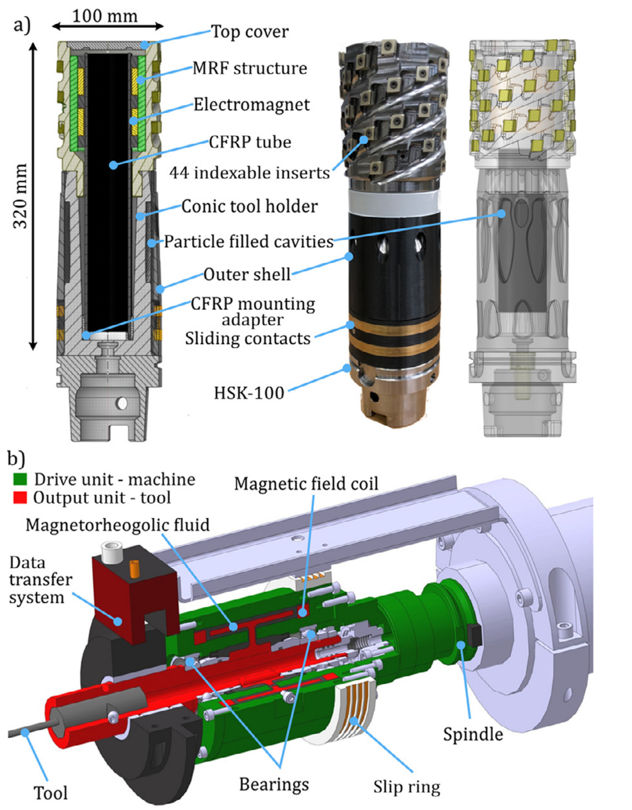

Fig. 34. a) Large shell mill with a passive friction damper and an active MRF damper [186], b) Adaptronic tool holder with MRF [282].

7.3. Machining applications with additional axes

Actuators in tooling systems are also used to machine parts with complex geometries that might not be machined by conventional machine tools. Examples are non-circular holes, chambers, trumpet-shaped boreholes, noncircular shapes, and dimple patterns on machined surfaces. Tooling systems with additional axes are used in a large variety of machining processes, e.g. milling, turning, boring, honing, and chambering [222]. The actuators are predominantly positioned in the tool or the tool body, in the tool holder, or operate with a rod going through the hollow spindle rotor.

The company Krauseco Werkzeugmaschinen developed a high-precision boring system to machine double trumpet-shaped bores for connecting rods (Fig. 35a). A push rod through the spindle tilts a membrane tool head with a special kinematics based on a flexure torsional joint, on which the tooling system is mounted. With this tilting control functionality, it is possible to create bore shapes for the connecting rod bores. Similarly for even simpler actuation and higher precision, the piezo boring head with flexure hinges developed by the IFT, TU Wien, enabled the machining of complex non-symmetrical geometries. Clamping and temperature-induced distortions are compensated by a closed-loop controller using built-in piezo actuators during the precision boring operation (cf. Fig. 35b). Another use of flexure joints was presented by Denkena et al. [63] with a piezo-actuated hybrid tooling system for the machining and structuring of liner bores. The cutting edge is mounted onto the tool, which is part of the elastic joint, and is placed with the piezo actuators inside the tool body. The piezo actuators control the radial displacement of the tool by joint kinematics. The distortion caused by the forces of the turning process must be considered when using a flexure joint with piezo actuation. However, in this particular application the forces resulting from the structuring process could be neglected.

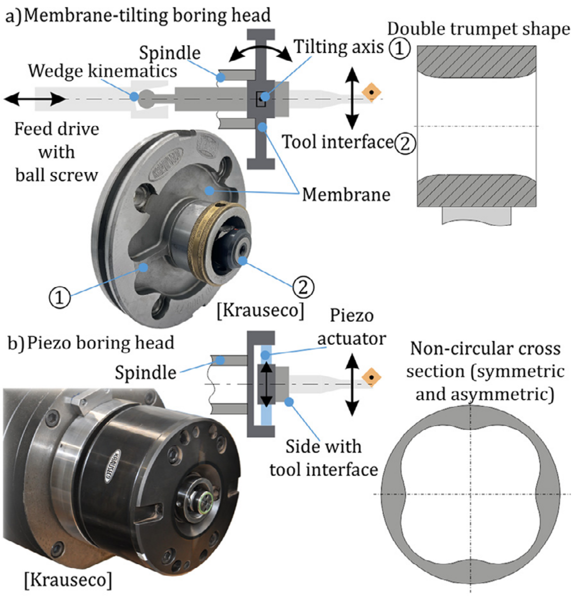

Fig. 35. Actuator-integrated tooling systems to machine various contours.

In some cases, it is desirable to machine slightly out of round bores, due to e.g., thermal expansion of the engine block in automotive applications. Panesso et al. [203] developed a system with a magnetic shape memory alloy actuator for fine boring of round cylinder bores. For the honing process in finishing and shaping the bores, several honing systems with actuators were developed. Drossel et al. [78,148] developed a form honing tool with piezo-actuators inside the tool to position the honing stone accurately while rotating at 800 rev/min. Furthermore, Drossel et al. [78] reported a hydraulically operated mechanical concept for the honing of out-of-round liner bores.

Push rods are also used in tooling systems related to the STS deep hole drilling process. Examples are bottom forming or chamber boring systems. Metzger et al. [172] presented a tooling system to machine the bottom of a deep hole drilled bore with a large diameter of D = 153 mm. This system was actuated by a through-spindle push rod to control the tool slider. The tool was positioned at the bottom of the bore by the machine's axis [172]. Schmidt et al. [222] reported a fully mechanical chamber boring system capable of machining long out of round bores with 2 m length. The desired cross-section of the bore was machined into a cam disk. Due to a complex mechanical drive system mounted at the back of the spindle, the profile of the cam disk was transmitted with a rotating rod through the spindle and the drilling tube through the tool body. In the tool body, a slider with an insert was actuated to follow the profile of the cam disk at each revolution.

There are a few commercial tooling systems, which use actuators for additional axes. The company Nagel Maschinen- und Werkzeugfabrik developed honing tools and honing machine systems to finish out of round line bores described by Drossel et al. in [78]. Furthermore, Mapal integrated at least three different physical principles in their tooling systems. The first principle was the contact stop method. The tool was pressed against a fixture and was actuated outward by a continuous feed. Another system consists of an electric drive and a gearbox, integrated into the tool holder which is called Tooltronic. The tooling system is programmable like an additional NC-axis as shown in Fig. 36.

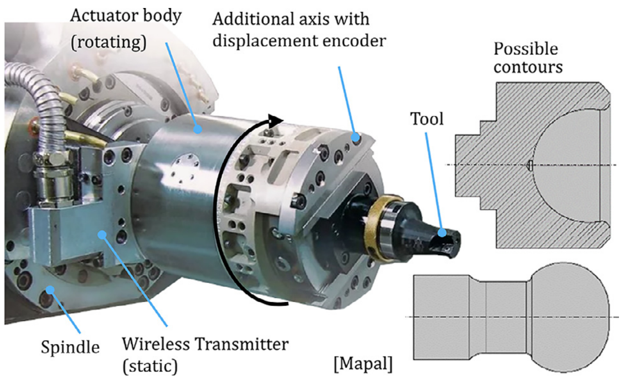

Fig. 36. Tooltronic system by Mapal.

A similar system provided by Ceratizit is called KOMtronic – U-Axis [96]. With these systems, complex internal and external contours even of non-rotationally symmetrical parts like in the machining of turbocharger housings, medical parts, or implants can be carried out by turning and boring operations on machining centers. Other systems use internal coolant pressure to position the insert for internal turning or boring operations. Fig. 37 shows a tool based on this working principle, which is used for the fine machining of the crankshaft-bearing seat of the 16-cylinder Bugatti Veyron engine 16.4. The internal coolant supply is utilized by other applications as well.

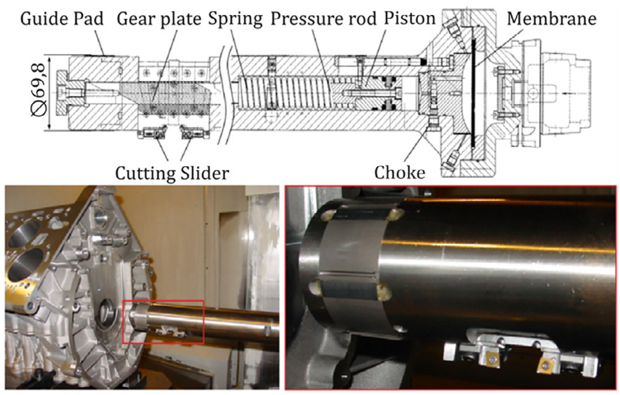

Fig. 37. Coolant pressure controlled actuator system for machining of an axial crankshaft bearing [30].

Colibri Spindles [227] developed several high-speed spindle systems inside tool holders. With these systems, small-diameter tools can be efficiently used in large main spindles. The high spindle speeds ranging up to 55,000 rev/min are generated through a turbine powered by the through spindle high-pressure coolant flow of the machine.

Nordström et al. [EP 0787050B1] invented a coolant actuated rear-end countersinking tool. The spring-loaded cartridge with the cutting edge is threaded through a bore. The tool unfolds when the internal coolant pressure is applied and allows for the machining of the rear end of the bore. Without the coolant pressure, the tool folds in and is easily retracted out of the bore.

8. Future enabling technologies and measures

The progress in sensor and actuator technology as well as electronics and communication technology accelerates the use of smart tooling systems. Most influencing trends can be identified in the area of sensor and actuator technology, in system design, or the field of data processing and system integration.

8.1. Sensor and actuator technology

Sensor development benefits from the advancements in their manufacturing technologies and signal processing methods. Recent advances in sensor and actuator technologies are powered by high-speed and low-cost electronic circuits, miniaturization, and the use of new materials or working principles. New design and integration concepts as well as signal processing methods, still relying on well-known measurement and actuation principles, can be used to achieve considerably improved sensor features. Low-cost analog-to-digital converters and signal processing increasingly shifted from the higher system integration level to the sensor. Digital signal processing improves the sensor's properties and enables the calibration to consider manufacturing variance or cross-sensitivity. Embedding other functions, such as online self-test or self-calibration, increases the system's reliability and reduces the initial operation and maintenance efforts. Emerging technologies in sensor development reveal from the application of additive films and materials [253]. This includes possible substrates, conductors, and insulators such as silicon-single crystal, polycrystalline, and amorphous silicon compounds (Si_xN_y, SiO_2, SiC etc.), metals and metallic compounds (Au, Cu, Al, ZnO, GaAs, IrO_x, CdS), ceramics (e.g., Al_20_3 and more complex ceramic compounds), or organics (diamond, polymers, etc.) [142]. New technologies offer high-volume manufacturable systems with small dimensions, lower power consumption, and higher reliability. Thereby, micro-electromechanical systems (MEMS) integrate sensors, mechanical, and electronic units including actuating functionality. Fig. 38 depicts the increasing complexity of MEMS.

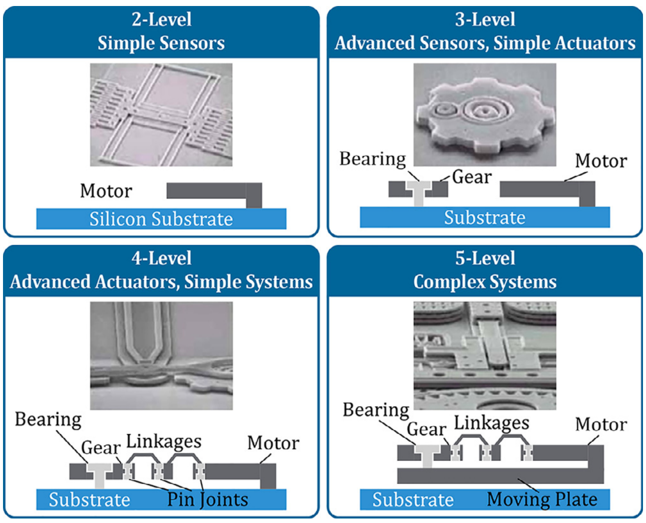

Fig. 38. MEMS device complexity by structural layers [161].

The development of sensor technology is predominantly based on advances in photolithography. The manufactured structures can be realized with a high aspect ratio. This property enables considerable advantages for sensor performance, such as higher sensitivity, displacement, mechanical robustness, and reduced noise. Three-dimensional mechanical structures are developed by a sequential deposition and selective removing of sacrificial layers. As an example, comb-drive-type actuators make use of a large number of fine integrated fingers. The generated force is related to the number of fingers as the capacitance is related to the area. In the field of sensor technology, additional measuring principles show interesting capabilities to be integrated into tooling systems like ionizing radiation sensors, pyroelectric detectors, spatially resolved acoustic spectroscopy (SRAS), and strain measurement based on carbon nanotubes [36].

8.2. Improvements in design

With a large number of components in sensor and actuator integrated tooling systems, which are indispensable to achieve the required functionality, the integration of the sensing and actuation features as well as the electric wiring of spatially distributed systems becomes complex and causes difficulties in the limited design space [86]. The arrangement of integrated systems needs to provide robust protection to withstand its operating environment while allowing access and connections to the physical domain. Printed circuit board laminates as substrate materials offer a variety of design options. Subsystems are attached to or embedded within the tooling system's surface or mechanical structure. The proximity of each die allows for improved system performance by providing low-noise wiring and in some cases eliminating unnecessary interconnections [115]. Advances in additive manufacturing lead to improved design and integration [82]. A reduction of wiring complexity can be achieved by using wireless technology. Wireless sensors can communicate via ultrasonic, infrared, or electromagnetic radiation signals. Energy-autonomous sensors will gain particular importance among wireless sensors because wires are no longer necessary even for electricity supply [44]. Another development direction for sensors and actuators is offered by 4D printing technology which applies the materials in such a way that they move or change their properties when a defined trigger is applied [295]. This approach of smart materials, which is still in the development stage, offers great potential for sensors but also for actuator development. Finally, microfluidic devices such as flow channels, pumps, and valves can be fabricated by micromachining or additive manufacturing techniques.

According to ElMaraghy et al. [85] the evolution and future of manufacturing systems are influenced by four different directions, (i) products, (ii) technology, (iii) business models, and (iv) manufacturing systems. This also reflects in the development of sensor and actuator-integrated tooling systems. On the side of the product, there will be more complex systems, which are highly embedded into the tooling system. In terms of technology, there will be a significant upscaling of the communication methods but also a significant advancement in artificial intelligence, machine, and deep learning methodology. Sensor and actuator-integrated tools will also play an important role in the area of business models as these systems have a positive influence on the efficiency improvement of manufacturing processes. Further integration of AI will allow for dynamic and cognitive process adjustments.

8.3. Trends in signal processing and system integration

The rapid development of communication networks and embedded system technology have become a focus in sensor and actuator-integrated tooling systems [280]. Embedded systems are generally defined as a special-purpose integration, which is based on computer technology, software, and sensor and actuator technology [81,124]. The adoption of wireless technologies will continue to increase across all vertical communication structures. All wireless technologies made significant improvements over the last few years encompassing, e.g., higher speed and bandwidth, lower latency, and higher quality of service. Especially in tooling systems with challenging connectivity requirements for rotating sensors, wireless solutions become more and more essential. Fig. 39 indicates the communication range of different wireless technologies.

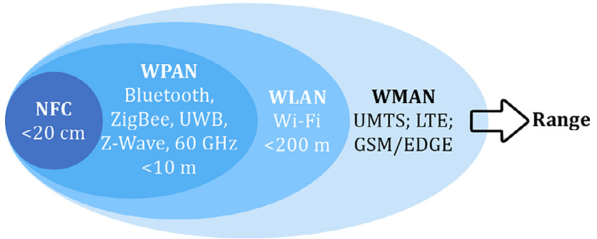

Fig. 39. Landscape of wireless technologies [17].

On-chip solutions at the gateway can manage the coexistence of different 2.4 GHz technologies to mitigate performance degradation and data loss. 5G, Wi-Fi 6, Bluetooth 5.0, and standard-based low-power wide-area network (LPWAN) protocols, mostly evolved in 2019, will take a big leap in terms of maturity and adoption. Release 16 of 5G standard includes new technologies for ultra-reliable low-latency communication and improvements in mobility, power consumption, and spectral efficiency. 5G is a key enabling technology for the deployment of cloud-based control systems [190]. Bluetooth 5.0 and its derivatives Bluetooth 5.1 and 5.2 introduce greatly enhanced range and throughput benefits.

Besides wireless data transfer, wireless power transfer (WPT) technology gains wide recognition [145]. WPT can be classified into radiative and non-radiative systems according to the form of the EM fields and the operational distance between the transmitter and the receiver [234]. The use of RFID at the 920 MHz band and the proliferation of mobile rechargeable batteries in tooling systems strive for wireless charging. As a typical scenario of radiative WPT, radio-frequency (RF) harvesting can be applied in wireless sensor applications [270]. Power can be transferred via electric fields by capacitive coupling between metal electrodes [156] or via magnetic fields by inductive coupling between coils [58]. Energy harvesting is suitable for battery-less, low-power devices. Other technologies generate electricity from weak power sources like ambient heat differences, vibration, sound, light, and radio waves [230].

9. Conclusions

This paper reviews sensor and actuator-integrated tooling systems and their applications in monitoring and control of metal cutting and grinding processes. The sensors, actuators, microcontrollers, power supply, signal processing, and data communication technologies, which constitute the foundations of sensors and actuator-integrated smart tooling systems, are explained with examples from the machining industry. The sample applications include tool wear and tool breakage monitoring, chatter detection and avoidance, adaptive force and deflection control, thermal compensation, and precision machining of parts with complex geometries. Sensors are mainly based on strain gages, piezo-elements, thermo-couples, eddy current and capacitive probes, and spindle or feed drive current extracted from the CNC systems. Depending on each application, the actuators consists of shape memory alloys, piezo elements, and electrical motors. The sensor signal processing and actuation algorithms can either be executed within the microprocessors embedded in the tooling systems or external computers. It is shown that the application of smart tooling systems enhances the productivity, robustness, and accuracy of machining operations. As a result, there is a strong trend to develop intelligent, self-adjusting, and thus unattended machining operations where smart tooling systems play an important role.

There are still significant challenges to achieving a highly reliable and robust smart tooling system. The actuators must be more miniaturized to integrate them into cutting tools and holders. The signal transmission must be wireless with low latency and high frequency, and the power must be either transmitted without wire or through energy harvesting techniques which are challenging. It is desirable to process all data within the microcontroller embedded in the tooling system to make them modular and independent of the machine tool. The integration of the smart tooling systems into machine tools must be as modular as possible with easy-to-use human interfaces on production floors. The sensor and actuator integrated tooling technologies are expected to enhance in parallel to advances in electronics, wireless signal and power transmission, smart materials for actuators, and sensor technologies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank the CIRP community as well as mentioned industrial partners for numerous contributions. Special thanks are dedicated to P. Georgi, R. Schmidt, S. Michel, M. Ettrichrätz, D. Leitner, C. Ramsauer for the support in the preparation of this paper.

References

[1] Abele E, Altintas Y, Brecher C (2010) Machine Tool Spindle Units. *CIRP Annals* 59 (2):781–802.
[2] Abele E, Bretz A (2017) Werkzeugverlagerung beim Reiben: Measuring The Tool Deviation During Reaming With Sensoric Tools. *wt* 107(01-02):21–26.
[3] Abele E, Grosch T, Schaupp E (2016) Smart Tool*/Smart Tool - Intelligent Sensor-Based Tool Management. *wt* 106(03):106–110.
[4] Abele E, Haydn M, Grosch T (2016) Adaptronic Approach For Modular Long Projecting Boring Tools. *CIRP Annals* 65(1):393–396.
[5] Abele E, Schiffler A, Rothenbücher S (2007) System Identification During Milling Via Active Magnetic Bearing. *Prod Eng Res Devel* 1(3):309–314.
[6] Abellan-Nebot JV, Romero Subirón F (2010) A Review Of Machining Monitoring Systems Based On Artificial Intelligence Process Models. *International Journal of Advanced Manufacturing Technology* 47(1-4):237–257.
[7] Aghazadeh F, Tahan A, Thomas M (2018) Tool Condition Monitoring Using Spectral Subtraction And Convolutional Neural Networks In Milling Process. *International Journal of Advanced Manufacturing Technology* 98(9-12):3217–3227.
[8] Aheleroff S, Xu X, Zhong RY, Lu Y (2021) Digital Twin as a Service (DTaaS) in Industry 4.0: An Architecture Reference Model. *Advanced Engineering Informatics* 47:101225.
[9] Aivaliotis P, Georgoulias K, Arkouli Z, Makris S (2019) Methodology For Enabling Digital Twin Using Advanced Physics-Based Modelling In Predictive Maintenance. *Procedia CIRP* 81:417–422.
[10] Akhil CS, Ananthavishnu MH, Akhil CK, Afeez PM, Akhilesh R, Rahul R (2017) Measurement of Cutting Temperature During Machining. *IOSR Journal of Mechanical and Civil Engineering* 13(2):108–122.
[11] Albrecht A, Park SS, Altintas Y, Pritschow G (2005) High Frequency Bandwidth Cutting Force Measurement In Milling Using Capacitance Displacement Sensors. *International Journal of Machine Tools and Manufacture* 45(9):993–1008.
[12] Altintas Y, Aslan D (2017) Integration Of Virtual And On-Line Machining Process Control And Monitoring. *CIRP Annals* 66(1):349–352.
[13] Altintas Y, Lappin D, van Zyl D, Östling D (2021) Automatically tuned Boring Bar System. *CIRP Annals* 70(1):313–316.
[14] Altintas Y, Park SS (2004) Dynamic Compensation of Spindle-Integrated Force Sensors. *CIRP Annals* 53(1):305–308.
[15] Altintas Y, Woronko A (2002) A Piezo Tool Actuator for Precision Turning of Hardened Shafts. *CIRP Annals* 51(1):303–306.
[16] Altintas Y, Yang J, Kilic ZM (2019) Virtual Prediction And Constraint Of Contour Errors Induced By Cutting Force Disturbances On Multi-Axis CNC Machine Tools. *CIRP Annals* 68(1):377–380.
[17] Andrusenko J, Burbank J, Ouyang F (2015) Future Trends in Commercial Wireless Communications and Why They Matter to the Military. *Johns Hopkins APL Technical Digest* 33(1):6–15.
[18] Apicella V, Clemente CS, Davino D, Leone D, Visone C (2019) Review of Modeling and Control of Magnetostrictive Actuators. *Actuators* 8(2):45.
[19] Aralikatti SS, Ravikumar KN, Kumar H (2019) Fault Diagnosis Of Single-Point Cutting Tool Using Vibration Signal By Rotation Forest Algorithm. *SN Appl Sci* 1(9).
[20] Arizmendi M, Campa FJ, Fernández J, López de Lacalle LN, Gil A, Bilbao E, Veiga F, Lamikiz A (2009) Model For Surface Topography Prediction In Peripheral Milling Considering Tool Vibration. *CIRP Annals* 58(1):93–96.
[21] Aslan D, Altintas Y (2018) On-Line Chatter Detection In Milling Using Drive Motor Current Commands Extracted From CNC. *International Journal of Machine Tools and Manufacture* 132:64–80.
[22] Aslan D, Altintas Y (2018) Prediction of Cutting Forces in Five-Axis Milling Using Feed Drive Current Measurements. *IEEE/ASME Transactions on Mechatronics* 23 (2):833–844.
[23] Babatain W, Bhattacharjee S, Hussain AM, Hussain MM (2021) Acceleration Sensors: Sensing Mechanisms, Emerging Fabrication Strategies, Materials, and Applications. *ACS Appl Electron Mater* 3(2):504–531.
[24] Baillieul J, Antsaklis PJ (2007) Control and Communication Challenges in Networked Real-Time Systems. *Proceedings of the IEEE* 95(1):9–28.
[25] Barkovskis N, Ozols K, Elsts A (2021) Survey of Low-Power Wireless Network Technologies for the Internet of Things. *Aut Control Comp Sci* 55(2):177–194.
[26] Basir R, Qaisar S, Ali M, Aldwairi M, Ashraf MI, Mahmood A, Gidlund M (2019) Fog Computing Enabling Industrial Internet of Things: State-of-the-Art and Research Challenges. *Sensors (Basel, Switzerland)* 19(21).

[27] Basti A, Obikawa T, Shinozuka J (2007) Tools With Built-In Thin Film Thermocouple Sensors For Monitoring Cutting Temperature. *International Journal of Machine Tools and Manufacture* 47(5):793–798.

[28] Biehl S, Lüthje H, Bandorf R, Sick J-H (2006) Multifunctional Thin Film Sensors Based On Amorphous Diamond-Like Carbon For Use In Tribological Applications. *Thin Solid Films* 515(3):1171–1175.

[29] Biehl S, Rumposch C, Bräuer G, Hoffmeister H-W, Luig M (2014) Development Of A Novel Piezoresistive Thin Film Sensor System Based On Hydrogenated Carbon. *Microsystem Technologies* 20(4-5):989–993.

[30] Biermann D, Bleicher F, Heisel U, Klocke F, Möhring H-C, Shih A (2018) Deep Hole Drilling. *CIRP Annals* 67(2):673–694.

[31] Bijami E, Farsangi MM (2019) A Distributed Control Framework And Delay-Dependent Stability Analysis For Large-Scale Networked Control Systems With Non-Ideal Communication Network. *Transactions of the Institute of Measurement and Control* 41(3):768–779.

[32] Bleicher F, Brier J (2016) Schwingungsunterstützte Schleifbearbeitung. *Schweizer Schleif-Symposium* .

[33] Bleicher F, Leder N, Schörghofer P, Ramsauer C, Oswald R (2009) Cognitive Machining By Sensor Integration In Tooling System. *The Proceedings of MTTRF 2019 Annual Meeting* .

[34] Bleicher F, Ramsauer C, Oswald R, Leder N, Schörghofer P (2020) Method For Determining Edge Chipping In Milling Based On Tool Holder Vibration Measurements. *CIRP Annals* 69(1):101–104.

[35] Bleicher F, Wiesinger G, Kumpf C, Finkeldei D, Baumann C, Lechner C (2018) Vibration Assisted Drilling of CFRP/Metal Stacks At Low Frequencies And High Amplitudes. *Prod Eng Res Devel* 12(2):289–296.

[36] Böttger S, Dietz F, Pankenin E, Dahra N, Kaulfersch E, Gromala P, Hermann S (2021) Heterosystem-Integrated Carbon Nanotube Sensors For On-ASIC Condition_Monitoring. VDE Verlag, *(Ed.).* MikroSystemTechnik Congress 2021, .

[37] Brecher C, Eckel H-M, Motschke T, Fey M, Epple A (2019) Estimation Of The Virtual Workpiece Quality By The Use Of A Spindle-Integrated Process Force Measurement. *CIRP Annals* 68(1):381–384.

[38] Brehl DE, Dow TA (2008) Review Of Vibration-Assisted Machining. *Precision Engineering* 32(3):153–172.

[39] Bretz A, Abele E, Weigold M (2020) Measuring The Bore Straightness During Reaming With Sensoric Tools. *Prod Eng Res Devel* 14(4):535–544.

[40] Brier J, Bleicher F (2021) Design Of A Contactless Powered And Piezoelectric-Actuated Tool For Non-Resonant Low-Frequency Vibration-Assisted Machining Of Brittle-Hard Materials. *International Journal of Advanced Manufacturing Technology* : 1–11.

[41] Brinksmeier E, Heinzel C, Meyer L (2005) Development and Application of a Wheel Based Process Monitoring System in Grinding. *CIRP Annals* 54(1):301–304.

[42] Bruckner D, Blair R, Stanica M-P, Ademaj A, Skeffington W, Kutscher D, Schriegel S, Wilmes R, Wachswender K, Leurs L, Seewald M, Hummen R, Liu E-C, Ravikumar S. *OPC UA TSN A new Solution for Industrial Communication*. https://www.intel.com/content/dam/support/us/en/programmable/support-resources/bulk-container/pdfs/literature/wp/opc-ua-tsn-solution-industrial-comm-wp.pdf (accessed on 14.09.2022).

[43] Bulla B, Klocke F, Dambon O, Hünten M (2012) Ultrasonic Assisted Diamond Turning of Hardened Steel for Mould Manufacturing. *Advances in Abrasive Techn VI* 516:437–442.

[44] Bulst W-E, Fischerauer G, Reindl L (1998) State Of The Art In Wireless Sensing With Surface Acoustic Waves. *IECON '98. Proceedings of the 24th Annual Conference of the IEEE Industrial Electronics Society (Cat. No.98CH36200)*, 2391–2396.

[45] Byrne G, Dornfeld D, Inasaki I, Ketteler G, König W, Teti R (1995) Tool Condition Monitoring (TCM) — The Status of Research and Industrial Application. *CIRP Annals* 44(2):541–567.

[46] Byrne G, O'Donnell GE (2007) An Integrated Force Sensor Solution for Process Monitoring of Drilling Operations. *CIRP Annals* 56(1):89–92.

[47] Caliskan H, Kilic ZM, Altintas Y (2018) On-Line Energy-Based Milling Chatter Detection. *Journal of Manufacturing Science and Engineering* 140(11):111012.

[48] Campanella CE, Cuccovillo A, Campanella C, Yurt A, Passaro VMN (2018) Fibre Bragg Grating Based Strain Sensors: Review of Technology and Applications. *Sensors (Basel)* 18(9):3115.

[49] Campidelli AFV, Lima HV, Abrão AM, Maia AAT (2019) Development Of A Wireless System For Milling Temperature Monitoring. *International Journal of Advanced Manufacturing Technology* 104(1-4):1551–1560.

[50] Cao H, Zhang X, Chen X (2017) The Concept And Progress Of Intelligent Spindles: A Review. *International Journal of Machine Tools and Manufacture* 112:21–52.

[51] Ceyssens F, Sadeghpour S, Fujita H, Puers R (2019) Actuators: Accomplishments, Opportunities And Challenges. *Sensors and Actuators A: Physical* 295:604–611.

[52] Chen W, Huo D, Shi Y, Hale JM (2018) State-Of-The-Art Review On Vibration-Assisted Milling: Principle, System Design, And Application. *International Journal of Advanced Manufacturing Technology* 97(5-8):2033–2049.

[53] Chen Y-L, Chen F, Li Z, Zhang Y, Ju B, Lin H (2021) Three-Axial Cutting Force Measurement In Micro/Nano-Cutting By Utilizing A Fast Tool Servo With A Smart Tool Holder. *CIRP Annals* 70(1):33–36.

[54] Cheng K, Niu Z-C, Wang RC, Rakowski R, Bateman R (2017) Smart Cutting Tools And Smart Machining: Development Approaches, And Their Implementation And Application Perspectives. *Chin J Mech Eng* 30(5):1162–1176.

[55] Childs PRN, Greenwood JR, Long CA (2000) Review Of Temperature Measurement. *Review of Scientific Instruments* 71(8):2959–2978.

[56] Choudhury SK, Goudimenko NN, Kudinov VA (1997) On-Line Control Of Machine Tool Vibration In Turning. *Int J Mach Tools Manufact* 37(6):801–811.

[57] Cimino C, Negri E, Fumagalli L (2019) Review Of Digital Twin Applications In Manufacturing. *Computers in Industry* 113:1–15.

[58] Covic GA, Boys JT (2013) Inductive Power Transfer. In: *Proc. IEEE*, 1276–1289.

[59] Cui Y, Liu Q, Wang L, Ding W, Wang XV, Liu Y, Li D (2018) Research On Milling Temperature Measuring Tool Embedded With NiCr/NiSi Thin Film Thermocouple. *Procedia CIRP* 72:1457–1462.

[60] Cui YX, Sun BY, Ding WY, Sun FD (2009) Development Of Multilayer Composition Thin Film Thermocouple Cutting Temperature Sensor Based On Magnetron Sputtering. *Advanced Materials Research* : 69–70. 515–9.

[61] Dahlmann D, Denkena B (2017) Hybrid Tool For High Performance Structuring And Honing Of Cylinder Liners. *CIRP Annals* 66(1):113–116.

[62] Dahnel AN, Ascroft H, Barnes S (2016) The Effect Of Varying Cutting Speeds On Tool Wear During Conventional And Ultrasonic Assisted Drilling (UAD) Of Carbon Fibre Composite (CFC) And Titanium Alloy Stacks. *Procedia CIRP* 46:420–423.

[63] Denkena B, Bergmann B, Handrup M (2020) Piezo-Actuated Hybrid Tool For The Micro Structuring Of Cylinder Liners In An Energy-Efficient Process Chain. *Procedia Manufacturing* 52:138–143.

[64] Denkena B, Dahlmann D, Boujnah H (2016) Sensory Workpieces For Process Monitoring – An Approach. *Procedia Technology* 26:129–135.

[65] Denkena B, Flöter F (2012) Adaptive Cutting Force Control On A Milling Machine With Hybrid Axis Configuration. *Procedia CIRP* 4:109–114.

[66] Denkena B, Gümmer O (2012) Process Stabilization With An Adaptronic Spindle System. *Prod Eng Res Devel* 6(4-5):485–492.

[67] Denkena B, Harms A (2004) A Tool Adaptor For Vibration Damping in CNC-Lathes International Seminar On Manufacturing Systems. In: *Proceedings of the 37th CIRP International Seminar on Manufacturing Systems: Digital enterprises, production networks*, 127–131.

[68] Denkena B, Möhring H-C, Will J-C (2004) Design And Layout Of An Adaptronic Spindle System. In: *Proceedings of the 37th CIRP International Seminar on Manufacturing Systems: Digital enterprises, production networks*, 111–118.

[69] Denkena B, Möhring H-C, Will J-C (2007) Tool Deflection Compensation With An Adaptronic Milling Spindle. *International Conference On Smart Machining Systems*,.

[70] Denkena B, Morke T (2017) *Cyber-Physical and Gentelligent Systems in Manufacturing and Life Cycle: Genetics and Intelligence - Keys to Industry 4.0*, Elsevier ScienceSaint Louis.

[71] Dimla DE, Lister PM (2000) On-Line Metal Cutting Tool Condition Monitoring. *International Journal of Machine Tools and Manufacture* 40(5):739–768.

[72] Dini G, Tognazzi F (2007) Tool Condition Monitoring In End Milling Using A Torque-Based Sensorized Toolholder. In: *Proceedings of the Institution of Mechanical Engineers, Part B: J. of Engineering Manufacture*, 11–23.

[73] Dohner JL, Lauffer JP, Hinnerichs TD, Shankar N, Regelbrugge M, Kwan C-M, Xu R, Winterbauer B, Bridger K (2004) Mitigation Of Chatter Instabilities In Milling By Active Structural Control. *Journal of Sound and Vibration* 269(1-2):197–211.

[74] Droeder K, Hoffmeister H-W, Grosse T (2017) Force-Controlled Form Honing Using A Piezo-Hydraulic Form Honing System. *CIRP Annals* 66(1):317–320.

[75] Drossel WG, Pagel K (2018) Actuator. in Produ TIAf. *CIRP Encyclopedia of Production Engineering*, Springer Berlin Heidelberg, Berlin, Heidelberg1–18.

[76] Drossel W-G, Bucht A, Pagel K, Mäder T, Junker T (2016) Adaptronic Applications In Cutting Machines. *Procedia CIRP* 46:303–306.

[77] Drossel W-G, Gebhardt S, Bucht A, Kranz B, Schneider J, Ettrichrätz M (2018) Performance Of A New Piezoceramic Thick Film Sensor For Measurement And Control Of Cutting Forces During Milling. *CIRP Annals* 67(1):45–48.

[78] Drossel W-G, Hochmuth C, Schneider R (2013) An Adaptronic System To Control Shape And Surface Of Liner Bores During The Honing Process. *CIRP Annals* 62 (1):331–334.

[79] Duan S, Wu J, Xia J, Lei W (2020) Innovation Strategy Selection Facilitates High-Performance Flexible Piezoelectric Sensors. *Sensors* 20(10):1–25.

[80] Dumss S, Weber M, Schwaiger C, Sulz C, Rosenberger P, Bleicher F, Grafinger M, Weigold M (2021) EuProGigant - A Concept Towards An Industrial System Architecture For Data-Driven Production Systems. *Procedia CIRP* 104:324–329.

[81] Dutt N, Jantsch A, Sarma S (2016) Toward Smart Embedded Systems: A Self-Aware System-On-Chip (SoC) Perspective. *ACM Trans Embed Comput Syst* 15(2):1–27.

[82] Dyson M (2022) *3D Electronics/Additive Electronics 2022-2032*, IDTechEx.

[83] Ehmer M, Khan F (2012) A Comparative Study Of White Box, Black Box And Grey Box Testing Techniques. *International Journal of Advanced Computer Science and Applications* 3(6):12–15.

[84] Elies S (2015) Performance Analysis of Commercial Accelerometers: A Parameter Review. *Sensors & Transducers Journal* (193):179–190.

[85] ElMaraghy H, Monostori L, Schuh G, ElMaraghy W (2021) Evolution And Future Of Manufacturing Systems. *CIRP Annals* 70(2):635–658.

[86] Elwenspoek M, Wiegerink R (2001) *Mechanical Microsensors*, SpringerBerlin, Heidelberg.

[87] Emmrich J, Bickel W, Denkena B, Ponick B (2013) Analysis Of An Integrated Electromagnetic Actuator Prototype. *Innovative Small Drives and Micro-Motor Systems* : 35–39.

[88] Fallah M, Moetakef-Imani B (2019) Adaptive Inverse Control Of Chatter Vibrations In Internal Turning Operations. *Mechanical Systems and Signal Processing* 129:91–111.

[89] Fan Y, Liu S, Liu X (2011) A New Predictive Control Systems With Network Delays In The Feedback And Forward Channels. *Chinese Control and Decision Conference* : 912–916.

[90] Faran E, Shilo D (2016) Ferromagnetic Shape Memory Alloys-Challenges, Applications, and Experimental Characterization. *Exp Techniques* 40:1005–1031.

[91] Ferrari P, Flammini A, Sisinni E, Rinaldi S, Brandao D, Rocha MS (2018) Delay Estimation Of Industrial IoT Applications Based On Messaging Protocols. *Ieee Transactions on Instrumentation and Measurement* 67(9):2188–2199.

[92] Ferreira M, Bierlich J, Becker M, Schuster K, Santos J, Frazão O (2014) Ultra-High Sensitive Strain Sensor Based On Post-Processed Optical Fiber Bragg Grating. *Fibers* 2(2):142–149.

[93] Feucht F, Ketelaer J, Wolff A, Mori M, Fujishima M (2014) Latest Machining Technologies Of Hard-To-Cut Materials By Ultrasonic Machine Tool. *Procedia CIRP* 14:148–152.

[94] Forschungskuratorium Maschinenbau e.V. *Dyna-Tool: Efficiency Improvement In Machining Of Complex Parts By Optimising The Tool System Dynamics*, 311st ed. .

[95] Fritsche A (2016) *Hub Design For The Reduction Of Process Forced Vibrations In High Performance Grinding*, Dissertation, Wien, TU Wien.

[96] Fronius J (2010) KomTronic® - Aktorische Werkzeugsysteme für die Einsatzerweiterung von Standard-Bearbeitungszentren. in Braun S, Maier W, Zirkelbach S, (Eds.) *Intelligent produzieren: Liber amicorum*, Springer, Berlin, Heidelberg, 128–134.

[97] Fuchs M, Bräunig M, Regel J, Dix M (2021) Sensory milling Chuck For Correction Of Thermal Tool Deformation By In-Process Temperature Measurement And Correction Value Calculation. *Conference Proceedings*, 160–168.

[98] Fuß M, Abrahams H, Buse B, Biermann D (2016) Production Of Deep Bore Holes With Non-Circular Profiles. *Advanced Materials Research* 1140:197–204.
[99] Gao J, Caliskan H, Altintas Y (2019) Sensorless Control Of A Three-Degree-Of-Freedom Ultrasonic Vibration Tool Holder. *Precision Engineering* 58:47–56.
[100] Garcia L, Jiménez JM, Taha M, Lloret J (2018) Wireless Technologies for IoT in Smart Cities. *Network Protocols and Algorithms* 10(1):23–64.
[101] García Plaza E, Núñez López PJ (2017) Surface Roughness Monitoring By Singular Spectrum Analysis Of Vibration Signals. *Mechanical Systems and Signal Processing* 84:516–530.
[102] Gautschi G (2002) *Piezoelectric Sensorics: Force Strain Pressure Acceleration and Acoustic Emission Sensors Materials and Amplifiers*, SpringerBerlin Heidelberg.
[103] Geisberger E, Broy M (2012) *agendaCPS: Integrierte Forschungsagenda Cyber-Physical Systems*, SpringerBerlin, Heidelberg.
[104] George B, Tan Z, Nihtianov S (2017) Advances in Capacitive, Eddy Current, and Magnetic Displacement Sensors and Corresponding Interfaces. *Ieee Transactions on Industrial Electronics* 64(12):9595–9607.
[105] Gerken JF, Klages N, Biermann D, Denkena B (2022) Development And Analysis Of A Mechatronic System For In-Process Monitoring And Compensation Of Straightness Deviation In BTA Deep Hole Drilling. *Mechanical Systems and Signal Processing* 170(108838):1–19.
[106] Ghosh AK, Ullah AS, Teti R, Kubo A (2021) Developing Sensor Signal-Based Digital Twins For Intelligent Machine Tools. *Journal of Industrial Information Integration* 24:1–18.
[107] Gianchandani YB, Tabata O, Zappe H (2008) *Comprehensive Microsystems*, ElsevierAmsterdam.
[108] Gödecke A, Zöls W, Bachmaier G (2013) Ratchet-Type Micro-Hydraulic Actuator To Mimic Muscle Behavior. *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, 3976–3981.
[109] Grabec I, Gradišek J, Govekar E (1999) A New Method for Chatter Detection in Turning. *CIRP Annals* 48(1):29–32.
[110] Granzer W, Kastner W (2012) Information Modeling In Heterogeneous Building Automation Systems. *2012 9th IEEE International Workshop on Factory Communication Systems*, IEEE, , 291–300.
[111] de Greef A, P Lambert, Delchambre A (2009) Towards Flexible Medical Instruments: Review Of Flexible Fluidic Actuators. *Precision Engineering* 33(4):311–321.
[112] Grosch T, Schloen J, Weigold M, Abele E (2019) SmartTool++: Test und Erweiterung eines intelligenten Werkzeugs. *Zeitschrift für wirtschaftlichen Fabrikbetrieb* 114(4):219–222.
[113] Grzenda M, Bustillo A (2019) Semi-Supervised Roughness Prediction With Partly Unlabeled Vibration Data Streams. *J Intell Manuf* 30:933–945.
[114] Guck JW, Reisslein M, Kellerer W (2016) Function Split Between Delay-Constrained Routing and Resource Allocation for Centrally Managed QoS in Industrial Networks. *Ieee Transactions on Industrial Informatics* 12(6):2050–2061.
[115] Guerrier P, Bowen C (2016) Additive Manufacturing For Next Generation Actuation. Recent Advances in Aerospace Actuation Systems and Components, Toulouse.
[116] Guo L, Gu H (2010) Robust Stability of Discrete Systems with Uncertainties and Random Delay. *2010 International Conference on Measuring Technology and Mechatronics Automation*, 291–294.
[117] Hamm M (2019) *Universelle und robuste Schwingsysteme für die spanende Bearbeitung*, Produktionstechnische Gespräche Dresden. 24.01.2019.
[118] Henry CP, Feuchtwanger J, Bono D, Marioni MA, Tello PG, Richard M, Allen SM, O'Handley RC (2001) AC Performance And Modeling Of Ferromagnetic Shape Memory Actuators. *Proceedings of SPIE* 4333:151–162.
[119] Hohlfeld K, Rhein S, Flössel M, Michaelis A, Gebhardt SE (2018) Manufacturing Technologies of Piezoelectric Components for Integration into Lightweight Structures. *Advanced Engineering Materials* 20(12):1–8. 1800431.
[120] Holmen KH (1969) *Adjustable Device For Damping Vibrations In Tool-Holding Rods, In Particular Boring Bars, In Machine Tools*. United States Patent US3598498A.
[121] Hong CC (2013) Application Of A Magnetostrictive Actuator. *Materials & Design* 46:617–621.
[122] Hou L, Bergmann NW (2012) Novel Industrial Wireless Sensor Networks for Machine Condition Monitoring and Fault Diagnosis. *Ieee Transactions on Instrumentation and Measurement* 61(10):2787–2798.
[123] Hoyne AC, Nath C, Kapoor SG (2015) On Cutting Temperature Measurement During Titanium Machining With an Atomization-Based Cutting Fluid Spray System. *Journal of Manufacturing Science and Engineering* 137(2):1–6. 024502.
[124] Hsiung P-A, Kuo T-W, Chang Y-H, Huang C-H (2016) Introduction To The Special Issue On Reconfigurable Cyber-Physical And Embedded System Design. *Journal of Systems Architecture* 62:39.
[125] Huber JE, Fleck NA, Ashby MF (1997) The Selection Of Mechanical Actuators Based On Performance Indices. *Proc R Soc Lond A* 453:2185–2205.
[126] Humphries JR, Malocha DC (2015) Wireless SAW Strain Sensor Using Orthogonal Frequency Coding. *IEEE Sensors Journal* 15(10):5527–5534.
[127] Hussein R, Sadek A, Elbestawi MA, Attia MH (2018) Low-Frequency Vibration-Assisted Drilling Of Hybrid CFRP/Ti6Al4V Stacked Material. *International Journal of Advanced Manufacturing Technology* 98:2801–2817.
[128] Ismail MIM, Dziyauddin RA, Ahmad R, Ahmad N, Ahmad NA, Hamid AMA (2021) A Review of Energy Harvesting in Localization for Wireless Sensor Node Tracking. *IEEE Access* 9:60108–60122.
[129] Jani JM, Leary M, Subic A (2017) Designing Shape Memory Alloy Linear Actuators: A Review. *Journal of Intelligent Material Systems and Structures* 28(13):1699–1718.
[130] Jiao F, Li Y, Wang D, Tong J, Niu Y (2021) Development Of A Low-Frequency Vibration-Assisted Drilling Device For Difficult-To-Cut Materials. *International Journal of Advanced Manufacturing Technology* 116:3517–3534.
[131] John S, Sirohi J, Wang G, Wereley NM (2007) Comparison of Piezoelectric, Magnetostrictive, and Electrostrictive Hybrid Hydraulic Actuators. *Journal of Intelligent Material Systems and Structures* 18:1035–1048.
[132] Kalman RE (1960) On The General Theory Of Control Systems. *IFAC Proceedings Volumes* 1(1):491–502.
[133] Karhu M, Lindroos T (2010) Long-Term Behaviour Of Binary Ti–49.7Ni (at.%) SMA Actuators—The Fatigue Lives And Evolution Of Strains On Thermal Cycling. *Smart Materials and Structures* 19(11):1–10. 115019.
[134] Karpuschewski B, Wehmeier M, Inasaki I (2000) Grinding Monitoring System Based on Power and Acoustic Emission Sensors. *CIRP Annals* 49(1):235–240.
[135] Kerrigan K, Thil J, Hewison R, O'Donnell GE (2012) An Integrated Telemetric Thermocouple Sensor for Process Monitoring of CFRP Milling Operations. *Procedia CIRP* 1:449–454.
[136] Kesriklioglu S (2018) *Prediction and Measurement of Tool-chip Interface Temperature with Instrumented Cutting Tools*, Dissertation, University of Wisconsin-Madison.
[137] Kester W (2005) Strain, Force, Pressure and Flow Measurements. *Op Amp Applications Handbook*, Elsevier, 247–256.
[138] Khajehzadeh M, Boostanipour O, Amiri S, Razfar MR (2020) The Influence Of Ultrasonic Elliptical Vibration Amplitude On Cutting Tool Flank Wear. In: *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 1499–1512.
[139] Komet Group. *Forschungsbericht zum Verbundprojekt "Bauteilgerechte Maschinenkonfiguration in der Fertigung durch Cyber-Physische Zusatzmodule", Kurztitel: BaZMod*, Besigheim.
[140] Königsberg J, Reiners J, Ponick B, Denkena B, Bergmann B (2018) Highly Dynamic Spindle Integrated Magnet Actuators for Chatter Reduction. *Int J Automation Technol* 12(5):669–677.
[141] Koren Y, Pasek ZJ, Szuba P (1999) Design of a Precision, Agile Line Boring Station. *CIRP Annals* 48(1):313–316.
[142] Kovacs GTA (1998) *Micromachined Transducers Sourcebook*, WCB McGraw-Hill-Boston, Mass.
[143] Kritzinger W, Karner M, Traar G, Henjes J, Sihn W (2018) Digital Twin in manufacturing: A Categorical Literature Review And Classification. *IFAC-PapersOnLine* 51 (11):1016–1022.
[144] Kumar MN, Subbu SK, Krishna PV, Venugopal A (2014) Vibration Assisted Conventional and Advanced Machining: A Review. *Procedia Engineering* 97:1577–1586.
[145] Kurs A, Karalis A, Moffatt R, Joannopoulos JD, Fisher P, Soljacic M (2007) Wireless Power Transfer Via Strongly Coupled Magnetic Resonances. *Science* 317 (5834):83–86.
[146] Kus A, Isik Y, Cakir MC, Coşkun S, Özdemir K (2015) Thermocouple and Infrared Sensor-Based Measurement Of Temperature Distribution In Metal Cutting. *Sensors* 15(1):1274–1291.
[147] Kusiak A (2018) Smart Manufacturing. *International Journal of Production Research* 56(1-2):508–517.
[148] Lauwers B, Klocke F, Klink A, Tekkaya AE, Neugebauer R, Mcintosh D (2014) Hybrid Processes In Manufacturing. *CIRP Annals* 63(2):561–583.
[149] Lazoglu I, Poulachon G, Ramirez C, Akmal M, Marcon B, Rossi F, Outeiro JC, Krebs M (2017) Thermal Analysis in Ti-6Al-4V Drilling. *CIRP Annals* 66(1):105–108.
[150] Le Coz G, Marinescu M, Devillez A, Dudzinski D, Velnom L (2012) Measuring Temperature Of Rotating Cutting Tools: Application to MQL Drilling And Dry Milling Of Aerospace Alloys. *Applied Thermal Engineering* 36:434–441.
[151] Lee J, Bagheri B, Kao H-A (2015) A Cyber-Physical Systems Architecture For Industry 4.0-Based Manufacturing Systems. *Manufacturing Letters* 3:18–23.
[152] Leonardi L, Patti G, Lo Bello L (2018) Multi-Hop Real-Time Communications Over Bluetooth Low Energy Industrial Wireless Mesh Networks. *IEEE Access* 6:26505–26519.
[153] Li D, Cao H, Chen X (2021) Fuzzy Control Of Milling Chatter With Piezoelectric Actuators Embedded To The Tool Holder. *Mechanical Systems and Signal Processing* 148:107190.
[154] Li J, Tao B, Huang S, Yin Z (2019) Cutting Tools Embedded With Thin Film Thermocouples Vertically To The Rake Face For Temperature Measurement. *Sensors and Actuators A: Physical* 296:392–399.
[155] Li L, Li B, Ehmann KF, Li X (2013) A Thermo-Mechanical Model Of Dry Orthogonal Cutting And Its Experimental Validation Through Embedded Micro-Scale Thin Film Thermocouple Arrays In PCBN Tooling. *International Journal of Machine Tools and Manufacture* 70:70–87.
[156] Li S, Liu Z, Zhao H, Zhu L, Shuai C, Chen Z (2016) Wireless Power Transfer by Electric Field Resonance and Its Application in Dynamic Charging. *IEEE Transactions on Industrial Electronics* 63(10):6602–6612.
[157] Liang SY, Hecker RL, Landers RG (2004) Machining Process Monitoring and Control: The State-of-the-Art. *Journal of Manufacturing Science and Engineering* 126 (2):297–310.
[158] Lisboa PJG, et al. (2013) Interpretability in Machine Learning – Principles and Practice. in Hutchison D, Kanade T, Kittler J, Kleinberg JM, Mattern F, Mitchell JC, (Eds.) *Fuzzy Logic and Applications*, Springer International Publishing. Cham,, 15–21.
[159] Liu C, Xu X (2017) Cyber-physical Machine Tool – The Era of Machine Tool 4.0. *Procedia CIRP* 63:70–75.
[160] Liu Y-P, Kilic ZM, Altintas Y (2022) Monitoring Of In-Process Force Coefficients And Tool Wear. *CIRP Journal of Manuf Science a Techn* 38:105–119.
[161] *An Introduction to MEMS (Micro-Electromechanical Systems)*, Loughborough University.
[162] Lu X, Chen F, Altintas Y (2014) Magnetic Actuator For Active Damping Of Boring Bars. *CIRP Annals* 63(1):369–372.
[163] Luenberger DG (1964) Observing the State of a Linear System. *IEEE Trans Mil Electron* 8(2):74–80.
[164] Luo M, Luo H, Axinte D, Liu D, Mei J, Liao Z (2018) A Wireless Instrumented Milling Cutter System With Embedded PVDF Sensors. *Mechanical Systems and Signal Processing* 110:556–568.
[165] Luo W, Hu T, Ye Y, Zhang C, Wei Y (2020) A Hybrid Predictive Maintenance Approach For CNC Machine Tool Driven By Digital Twin. *Robotics and Computer-Integrated Manufacturing* 65:101974.
[166] Ma W, Yu J, Yang Y, Wang Y (2021) Optimization and Tuning of Passive Tuned Mass Damper Embedded in Milling Tool for Chatter Mitigation. *JMMP* 5(1):2.
[167] Mahnke W, Leitner S-H, Damm M (2009) *OPC Unified Architecture*, Springer Science & Business Media.
[168] Maiwald D, Bucht A, Zorn W, Drossel W-G (2020) Development Approach of Actuators for High Loads Based on Shape Memory Alloys. *ASME 2020 Conference on Smart Materials Adaptive Structures, and Intelligent Systems*,.
[169] Matsubara A, Maeda M, Yamaji I (2014) Vibration Suppression Of Boring Bar By Piezoelectric Actuators And LR Circuit. *CIRP Annals* 63(1):373–376.

[170] Matsuda R, Shindou M, Hirogaki T, Aoyama E (2018) Monitoring of Rotational Vibration in Tap and Endmill Processes with a Wireless Multifunctional Tool Holder System. *Int J Automation Technol* 12(6):876–882.
[171] Mauthner G, Ehrendorfer M, Trautner T, Ramsauer C, Plakhotnik D, Bleicher F (2021) Method for Data-Driven NC-Code Optimization based on Dexel Material Removal Simulation and Tool Holder Vibration Measurements. *Procedia CIRP* 104:1131–1136.
[172] Metzger M, Fuß M, Biermann D (2019) Development of a New Machining Tool for Bottom Forming in Deep Bore Holes. in Schmitt R, Schuh G, (Eds.) *Advances in Production Research*, Springer International Publishing. Cham, , 270–277.
[173] Michel S, Biermann D, Kurkowski M, Spickenheuer A, Stommel M, Summe J, Herrmann H-G (2021) FKV-Bohrrohre mit strukturintegrierter Sensorik/Vibration damping And Process Monitoring in BTA Deep Hole Drilling Using Fiber Composites – FRP Drill Tubes With Structure-Integrated sensors. *wt* 111(11-12):846–850.
[174] Michel S, Kurkowski M, Fuß M, Biermann D (2021) Stommel M Lightweight FRP Drill Tubes for Vibration Damping in BTA Deep Hole Drilling. *Conference Proceedings*, 221–229.
[175] Micheletti GF, Koenig W, Victor HR (1976) Process Tool Wear Sensors for Cutting Operations. *CIRP Annals* 25(2):483–496.
[176] Mihailov SJ (2012) Fiber Bragg Grating Sensors For Harsh Environments. *Sensors* 12(2):1898–1918.
[177] Mo H, Wang W, Xie M, Xiong J (2017) Modeling and Analysis of the Reliability of Digital Networked Control Systems Considering Networked Degradations. *IEEE Transactions on Automation Science and Engineering* 14(3):1491–1503.
[178] Mohith S, Upadhya AR, Navin KP, Kulkarni SM, Rao M (2021) Recent Trends In Piezoelectric Actuators For Precision Motion And Their Applications: A Review. *Smart Materials and Structures* 30(1):13002.
[179] Möhring H-C (2014) Monitoring. *CIRP Encyclopedia of Production Engineering*, Springer, Berlin, Heidelberg901–908.
[180] Möhring H-C, Eschelbacher S, Georgi P (2020) Fundamental Investigation On The Correlation Between Surface Properties And Acceleration Data From A Sensor Integrated Milling Tool. *Procedia Manufacturing* 52:79–84.
[181] Möhring H-C, Eschelbacher S, Georgi P (2021) Machine Learning Approaches For Real-Time Monitoring And Evaluation Of Surface Roughness Using A Sensory Milling Tool. *Procedia CIRP* 102:264–269.
[182] Möhring H-C, Litwinski KM, Gümmer O (2010) Process Monitoring With Sensory Machine Tool Components. *CIRP Annals* 59(1):383–386.
[183] Möhring H-C, Maier W, Werkle K (2018) Increasing the Accuracy of an Intelligent Milling Tool with Integrated Sensors. in Billington D, (Ed.) *Proceedings of the 18th International Conference of the European Society for Precision Engineering and Nanotechnology: June 4th-8th June 2018, Venice, IT*, euspen, Bedford, UK.
[184] Möhring H-C, Nguyen QP, Kuhlmann A, Lerez C, Nguyen LT, Misch S (2016) Intelligent Tools for Predictive Process Control. *Procedia CIRP* 57:539–544.
[185] Möhring H-C, Werkle K, Maier W (2020) Process Monitoring With A Cyber-Physical Cutting Tool. *Procedia CIRP* 93:1466–1471.
[186] Möhring H-C, Werkle KT (2022) Lightweight Semi-Actively Damped High Performance Milling Tool. *CIRP Annals* 71(1):353–356.
[187] Möhring H-C, Wiederkehr P, Erkorkmaz K, Kakinuma Y (2020) Self-Optimizing Machining Systems. *CIRP Annals* 69(2):740–763.
[188] Monostori L, Markus A, van Brussel H, Westkämpfer E (1996) Machine Learning Approaches to Manufacturing. *CIRP Annals* 45(2):675–712.
[189] Moriwaki T, Shamoto E (1991) Ultraprecision Diamond Turning of Stainless Steel by Applying Ultrasonic Vibration. *CIRP Annals* 40(1):559–562.
[190] Mourtzis D (2021) Smart Manufacturing and Tactile Internet Powered by 5G: Investigation of Current Developments, Challenges, and Future Trends. *Procedia CIRP* 104:1960–1969.
[191] MTConnect. *Standard — MTConnect*. www.mtconnect.org (accessed on 17.01.2022).
[192] Munoa J, Beudaert X, Dombovari Z, Altintas Y, Budak E, Brecher C, Stepan G (2016) Chatter Suppression Techniques In Metal Cutting. *CIRP Annals* 65(2):785–808.
[193] Negri E, Fumagalli L, Macchi M (2017) A Review of the Roles of Digital Twin in CPS-based Production Systems. *Procedia Manufacturing* 11:939–948.
[194] Nespoli A, Besseghini S, Pittaccio S, Villa E, Viscuso S (2010) The High Potential Of Shape Memory Alloys In Developing Miniature Mechanical Devices: A Review On Shape Memory Alloy Mini-Actuators. *Sensors and Actuators A: Physical* 158 (1):149–160.
[195] Neugebauer R, Denkena B, Wegener K (2007) Mechatronic Systems for Machine Tools. *CIRP Annals* 56(2):657–686.
[196] Neugebauer R, Hochmuth C, Schneider R (2014) Adaptronic Form Honing – Manufacturing Methods for Compensating Cylinder Bore Distortions. *Manufacturing Process Technology* 907:489–499.
[197] O'Neal GP, Min B-K, Pasek ZJ, Koren Y (2001) Integrated Structural/Control Design of Micro-Positioner for Boring Bar Tool Insert. *Journal of Intelligent Material Systems and Structures* 12(9):617–627.
[198] OPC Foundation. *Unified Architecture - OPC Foundation*. https://opcfoundation.org/about/opc-technologies/opc-ua/(accessed on 17.01.2022).
[199] OPC Foundation. *What is OPC?* https://opcfoundation.org/about/what-is-opc/.
[200] Ostasevicius V, Karpavicius P, Jurenas V, Cepenas M, Cesnavicius R, Eidukynas D (2020) Development Of Universal Wireless Sensor Node For Tool Condition Monitoring In Milling. *International Journal of Advanced Manufacturing Technology* 110(3-4):1015–1025.
[201] Öztürk T, Sarıkaya E, Weigold M (2021) Sensor-Integrated Tap Holder For Process Uncertainty Detection Based On Tool Vibration And Axial Length Compensation Sensors. *International Journal of Advanced Manufacturing Technology* 117(5-6):1905–1914.
[202] Pagel K, Drossel W-G (2017) Design and Experimental Validation of a Hybrid Actuator Based on Piezoceramics and Shape-Memory-Alloys. in Wulfsberg JP, Sanders A, (Eds.) *Small Machine Tools for Small Workpieces*, Springer International Publishing. Cham, , 89–102.
[203] Panesso M, Rau D, Pagel K, Böhm A, Drossel W-G Integration of Magnetic Shape Memory Alloy Actuator In Fine Boring Tool Positioning System. *Proceedings Vol. 11588, Active and Passive Smart Structures and Integrated Systems XV* 11588:115880Z.
[204] Park G, Bement MT, Hartman DA, Smith RE, Farrar CR (2007) The Use Of Active Materials For Machining Processes: A Review. *International Journal of Machine Tools and Manufacture* 47(15):2189–2206.
[205] Park SS, Altintas Y (2004) Dynamic Compensation of Spindle Dynamic Compensation of Spindle Integrated Force Sensors With Kalman Filter. *Journal of Dynamic Systems, Measurement, and Control* 126(3):443–452.
[206] Pauker F (2019) *UA Information Model Design OPC UA Informationsmodellierung für Cyber-Physical Production Systems*, OPCDissertation, TU Wien.
[207] Pecat O, Brinksmeier E (2014) Low Damage Drilling of CFRP/Titanium Compound Materials for Fastening. *Procedia CIRP* 13:1–7.
[208] Pedregosa F, Varoquaux G, Gramfort A, Michel V, Thirion B, Grisel O, Blondel M, Prettenhofer P, Weiss R, Dubourg V, Vanderplas J, Passos A, Cournapeau D, Brucher M, Perrot M, Duchesnay E (2011) Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research* 12:2825–2830.
[209] Plogmeyer M, González G, Biehl S, Schulze V, Bräuer G (2021) Wear-Resistive Thin-Film Sensors On Cutting Tools For In-Process Temperature Measurement. *Procedia CIRP* 101:85–88.
[210] Pons JL A comparative analysis of Piezoelectric and Magnetostrictive actuators in Smart Structures. *Boletin de la Sociedad Espanola de Ceramica y Vidrio*, pp. 146–154.
[211] Pons JL (2005) *Emerging Actuator Technologies: A Micromechatronic Approach*, WileyChichester.
[212] Pratt JR, Nayfeh AH (2001) Chatter Control And Stability Analysis Of A Cantilever Boring Bar Under Regenerative Cutting Conditions. *Philosophical Transactions of the Royal Society of London Series A: Mathematical, Physical and Engineering Sciences* 359(1781):759–792.
[213] Rahimi MH, Huynh HN, Altintas Y (2021) On-Line Chatter Detection In Milling With Hybrid Machine Learning And Physics-Based Model. *CIRP Journal of Manufacturing Science and Technology* 35:25–40.
[214] Ramsauer C, Bleicher F (2021) New Method For Determining Single Cutting Edge Breakage Of A Multi-Tooth Milling Tool Based On Acceleration Measurements Of An Instrumented Tool Holder. *Journal of Machine Engineering* 21(1).
[215] Raptis TP, Passarella A, Conti M (2019) Data Management in Industry 4.0: State of the Art and Open Challenges. *IEEE Access* 7:97052–97093.
[216] Rizal M, Ghani JA, Nuawi MZ, Haron CHC (2018) An Embedded Multi-Sensor System On The Rotating Dynamometer For Real-Time Condition Monitoring In Milling. *International Journal of Advanced Manufacturing Technology* 95(1-4):811–823.
[217] Sáez AJ, Polat E, Mandel C, Schüßler M, Kubina B, Scherer T, Lautenschläger N, Jakoby R (2016) Chipless Wireless Temperature Sensor for Machine Tools Based on a Dielectric Ring Resonator. *Procedia Engineering* 168:1231–1236.
[218] Sahota JK, Gupta N, Dhawan D (2020) Fiber Bragg Grating Sensors For Monitoring Of Physical Parameters: A Comprehensive Review. *Optical Engineering* 59 (06). 060901-X.
[219] Saleh MK, Ulasyar A, Lazoglu I (2021) Active Damping Of Chatter In The Boring Process Via Variable Gain Sliding Mode Control Of A Magnetorheological Damper. *CIRP Annals* 70(1):337–340.
[220] San-Juan M, Martín Ó, Santos F (2010) Experimental Study Of Friction From Cutting Forces In Orthogonal Milling. *International Journal of Machine Tools and Manufacture* 50(7):591–600.
[221] Sauer MS, Grosch T, Abele E (2014) *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 109, Smart Tool., 542–545.
[222] Schmidt R, Gerken JF, Fuß M, Biermann D (2019) Analysis Of Contour Accuracy And Process Forces Using A Chamber-Boring-System. *MM SJ* 2019(04):3316–3322.
[223] Schörghofer P, Bleicher F, Weiler T, Habersohn C (2017) Chatter Detection And Avoidance Using A Sensory Tool Holder. *34th Danubia-Adria Symposium on Advances in Experimental Mechanic*,.
[224] Schörghofer P, Pauker F, Leder N, Mangler J, Ramsauer C, Bleicher F (2019) Using sensory Tool Holder Data For Optimizing Production Processes. *Journal of Machine Engineering* 19(3):43–55.
[225] Schott A, Biehl S, Bräuer G, Herrmann C (2021) Thin Film Sensor Systems for Use in Smart Production. in Dröder K, Vietor T, (Eds.) *Technologies For Economic And Functional Lightweight Design*, Springer, Berlin, Heidelberg, 220–231.
[226] Schriegel S, Kobzan T, Jasperneite J (2018) Investigation On A Distributed SDN Control Plane Architecture For Heterogeneous Time Sensitive Networks. *14th IEEE International Workshop 2018*,.
[227] Schubert A, Harpaz O, Books B, Eckert U, Wertheim R (2013) HPC For Improved Efficiency On Standard Machine Tools By Using New Fluid-Driven Spindles. In: *Proceedings of the 11th Global Conference on Sustainable Manufacturing*,.
[228] Schur S (2008) *Mit axialem Pulsieren zu höherem Vorschub. Hochleistungs-Tiefbohren mit dem Axial-Pulsator*, WB Werkstatt und Betrieb. 24–28.
[229] Shankar N, Bridger K, Regelbrugge ME, Winfough WR Smart Spindle Unit For Active Chatter Suppression Of A Milling Machine: I. Overview, Fabrication And Assembly. Proceeding of SPIE, p. 160.
[230] Shinohara N (2021) Trends in Wireless Power Transfer: WPT Technology for Energy Harvesting, Mllimeter-Wave/THz Rectennas, MIMO-WPT, and Advances in Near-Field WPT Applications. *IEEE Microwave* 22(1):46–59.
[231] Shinozuka J, binti Jaharadak H (2016) Measurement of the Temperature Distribution at the Tool-Chip Interface by Using a Cutting Tool with Seven Pairs of Built-In Micro Cu/Ni Thermocouples. *Manufacturing Process Technology* 1136:586–591.
[232] Silge M, Kellerer T, Sattel T (2016) Design Concept For Frequency-Variable Electromagnetic Contactless Energy Transfer Systems Powering Vibrational Actuators In Rotary Machining. *IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, 1–5.
[233] Slavov V, Kimmelmann M, Heisel U (2015) Media, Data and Energy Transmission in Machine Tool Spindles: An FE Analysis of Implementation Possibilities. *AMM* 794:403–410.
[234] Song M, Belov P, Kapitanova P (2017) Wireless Power Transfer Inspired By The Modern Trends In Electromagnetics. *Applied Physics Reviews* 4(2):21102.
[235] Spiewak S (1992) Instrumented Milling Cutter for In-Process Measurement of Spindle Error Motion. *CIRP Annals* 41(1):429–432.
[236] Stampfer B, González G, Gerstenmeyer M, Schulze V (2021) The Present State of Surface Conditioning in Cutting and Grinding. *JMMP* 5(3):92.

[237] Standardization Council Industrie 4.0. Deutsches Institut für Normung, Deutsche Kommission Elektrotechnik, Elektronik, Informationstechnik. *German standardization roadmap industrie 4.0: DIN and DKE roadmap*, 4th ed. DKE Deutsche Kommission Elektrotechnik Elektronik Informationstechnik in DIN und VDEFrankfurt am Main.
[238] Stavropoulos P (2022) Digitization of Manufacturing Processes: From Sensing to Twining. *Technologies* 10(5):98.
[239] Ştefănescu DM, Anghel MA (2013) Electrical Methods For Force Measurement – A Brief Survey. *Measurement* 46(2):949–959.
[240] Stemmler S, Abel D, Schwenzer M, Adams O, Klocke F (2017) Model Predictive Control for Force Control in Milling. *IFAC-PapersOnLine* 50(1):15871–15876.
[241] Stoney R, Pullen T, Aldwell B, Gierlings S, Brockmann M, Geraghty D, Veselovac D, Klocke F, Donnell G (2014) Observations of Surface Acoustic Wave Strain and Resistive Strain Measurements on Broaching Tools for Process Monitoring. *Procedia CIRP* 14:66–71.
[242] Stroehla T, Dahlmann M (2021) Sattel T Electromagnetic Actuators: International Conference and Exhibition on New Actuator Systems and Applications: GMM Conference, February 17-19, 2021, online event. *Actuator* : 24–29.
[243] Subrahmanya K, Vadivuchezhian K, Chockappan N (2015) Experimental Verification of Effect of Adhesive Layer Thickness Used for Strain Gauge Mounting. *AMR* 1119:789–793.
[244] Sugita N, Ishii K, Furusho T, Harada K, Mitsuishi M (2015) Cutting Temperature Measurement By A Micro-Sensor Array Integrated On The Rake Face Of A Cutting Tool. *CIRP Annals* 64(1):77–80.
[245] Sun L, Liao W, Zheng K, Tian W, Liu J, Feng J (2021) Stability Analysis Of Robotic Longitudinal-Torsional Composite Ultrasonic Milling. *Chinese Journal of Aeronautics* 35(8):249–264.
[246] Sun Y, Huo Y Robust Static Output Feedback Control For Networked Control System With Random Time Delay. *2nd International Conference on Advanced Computer Control*, pp. 547–551.
[247] Suprock C, Nichols J (2009) A Low Cost Wireless High Bandwidth Transmitter For Sensor-Integrated Metal Cutting Tools And Process Monitoring. *Int J Mechatronics and Manufacturing Systems* 2.
[248] Venkatesan T, Pandya Haresh M (2013) Surface Acoustic Wave Devices and Sensors - A Short Review On Design and Modelling by Impulse Response. *J Environ Nanotechnol* 2(3):81–89.
[249] Teti R, Jawahir IS, Jemielniak K, Segreto T, Chen S, Kossakowska J (2006) Chip Form Monitoring through Advanced Processing of Cutting Force Sensor Signals. *CIRP Annals* 55(1):75–80.
[250] Teti R, Jemielniak K, O'Donnell G, Dornfeld D (2010) Advanced Monitoring Of Machining Operations. *CIRP Annals* 59(2):717–739.
[251] Teti R, Mourtzis D, D'Addona D, Caggiano A (2022) Process Monitoring Of Machining. *CIRP Annals* 71(2):529–552.
[252] Tillmann W, Vogli E, Herper J, Biermann D, Pantke K (2010) Development Of Temperature Sensor Thin Films To Monitor Turning Processes. *Journal of Materials Processing Technology* 210(5):819–823.
[253] Ting Y, Chen H-Y, Chen J-H, Suprapto Yu C-H (2021) Design And Performance Evaluation Of A Multi-Axis Thin-Film Sensor For Milling Process Measurement. *Sensors and Actuators A: Physical* 332:113147.
[254] Tlusty J, Andrews GC (1983) A Critical Review of Sensors for Unmanned Machining. *CIRP Annals* 32(2):563–572.
[255] Tong X, Liu Q, Pi S, Xiao Y (2020) Real-Time Machining Data Application And Service Based On IMT Digital Twin. *Journal of Intelligent Manufacturing* 31(5):1113–1132.
[256] Tönshoff HK, Wulfsberg JP, Kals H, König W, van Luttervelt CA (1988) Developments and Trends in Monitoring and Control of Machining Processes. *CIRP Annals* 37(2):611–622.
[257] Totis G, Wirtz G, Sortino M, Veselovac D, Kuljanic E, Klocke F (2010) Development Of A Dynamometer For Measuring Individual Cutting Edge Forces In Face Milling. *Mechanical Systems and Signal Processing* 24(6):1844–1857.
[258] Trabesinger S, Butzerin A, Schall D, Pichler R (2020) Analysis of High Frequency Data of a Machine Tool via Edge Computing. *Procedia Manufacturing* 45:343–348.
[259] Tramarin F, Mok AK, Han S (2019) Real-Time and Reliable Industrial Control Over Wireless LANs: Algorithms, Protocols, and Future Directions. *Proceedings of the IEEE* 107(6):1027–1052.
[260] Trevisan R, Costanzo A (2014) State-Of-The-Art Of Contactless Energy Transfer (CET) Systems: Design Rules And Applications. *Wireless Power Transfer* 1(1):10–20.
[261] Uehara K, Takeyama H (1973) New Attempts For Short Time Tool-Life Testing. *CIRP Annals* 22(1):23.
[262] Uhlmann E, Protz F (2019) Ultrasonic Assisted Peripheral Milling Of Fiber Reinforced Plastics In Consideration Of Clamping And Cutting Edge Geometry. *Procedia Manufacturing* 40:56–63.
[263] Vallejo AJ, Morales-Menéndez R, Alique JR (2008) Online Cutting Tool Condition Monitoring in Machining Processes using Artificial Intelligence. in Pecherkova P, Flidr M, Dunik J, (Eds.). Robotics Automation and Control. ISBN 978-953-7619-18-3 InTech. Rijeka
[264] van der Linden D, Granzer W, Kastner W OPC (2011) Unified Architecture (OPC UA) New Opportunities Of System Integration And Information Modelling In Automation Systems. *9th IEEE Internatonal Conference on Industrial Informatics*, 1–169.
[265] Vanparys M (2012) *Ultrasonic Assisted Grinding of Ceramic Components (Ultrasoon ondersteund slijpen van keramische componenten)*, Katholieke Universiteit Leuven.
[266] Varghese B, Pathare S, Gao R, Guo C, Malkin S (2000) Development of a Sensor-Integrated "Intelligent" Grinding Wheel for In-Process Monitoring. *CIRP Annals* 49(1):231–234.
[267] VDW – Verein Deutscher Werkzeugmaschinenfabriken e.V. *umati: Die universelle Schnittstelle für Werkzeugmaschinen*. www.umati.org/(accessed on 03.01.2020).
[268] Vicente J de, Klingenberg DJ, Hidalgo-Alvarez R (2011) Magnetorheological Fluids: A Review. *Soft Matter* 7(8):3701.
[269] Vieler H, Lechler A, Riedel O (2017) Architecture and Implementation of an Interface for Intelligent Tools in Machine Tools. *Procedia Manufacturing* 11:2077–2082.
[270] Visser HJ, Vullers RJM (2013) RF Energy Harvesting and Transport for Wireless Sensor Network Applications: Principles and Requirements. *Proceedings of the IEEE* 101(6):1410–1423.
[271] Volder M de, Reynaerts D (2010) Pneumatic And Hydraulic Microactuators: A Review. *Journal of Micromechanics and Microengineering* 20(4):43001.
[272] Wan S, Li X, Su W, Yuan J, Hong J, Jin X (2019) Active Damping Of Milling Chatter Vibration Via A Novel Spindle System With An Integrated Electromagnetic Actuator. *Precision Engineering* 57:203–210.
[273] Wan Nuha Wan Mansor, Nurul Hidayah Md Tahir. Tool Wear Condition Monitoring using Slip Ring and Accelerometer System in Milling AISI P20 Tool Steel. *Journal of Mechanical Engineering* : 63–72.
[274] Wang C, Hong G-Y, Li K-M, Young H-T (2017) A Miniaturized Nickel Oxide Thermistor via Aerosol Jet Technology. *Sensors* 17(11):2602.
[275] Wang C, Zhang X, Liu Y, Cao H, Chen X (2018) Stiffness Variation Method For Milling Chatter Suppression Via Piezoelectric Stack Actuators. *International Journal of Machine Tools and Manufacture* 124:53–66.
[276] Wang F, Shu S, Lin F (2016) Robust Networked Control of Discrete Event Systems. *IEEE Transactions on Automation Science and Engineering* 13 (4):1528–1540.
[277] Wang J, Zhang J, Feng P, Guo P, Zhang Q (2018) Feasibility Study of Longitudinal–Torsional-Coupled Rotary Ultrasonic Machining of Brittle Material. *Journal of Manufacturing Science and Engineering* 140(5):51008.
[278] Wang L, Alexander CA (2015) Big Data in Design and Manufacturing Engineering. *American Journal of Engineering and Applied Sciences* 8(2):223–232.
[279] Wang S, Rong W, Wang L, Xie H, Sun L, Mills JK (2019) A Survey Of Piezoelectric Actuators With Long Working Stroke In Recent Years: Classifications, Principles, Connections And Distinctions. *Mechanical Systems and Signal Processing* 123:591–605.
[280] Wang X, Wang Z, Huang W, Wen GQ, Zhang SL (2017) Summary of Embedded Systems Development. *Advances in Engineering Research* : 1442–1446.
[281] Wegert R, Alhamede MA, Guski V, Schmauder S, Möhring H-C (2022) Sensor-Integrated Tool for Self-Optimizing Single-Lip Deep Hole Drilling. *International Journal of Automation Technology* 16(2):126–137.
[282] Weinert K, Kersting M (2007) *Adaptronic Chatter Damping System for Deep Hole Drilling*, Digitally PublishedGaithersburg, Maryland, USA.
[283] Werschmoeller D, Ehmann K, Li X (2011) Tool Embedded Thin Film Microsensors for Monitoring Thermal Phenomena at Tool-Workpiece Interface During Machining. *Journal of Manufacturing Science and Engineering* 133(2):021007.
[284] Werschmoeller D, Li X (2011) Measurement Of Tool Internal Temperatures In The Tool–Chip Contact Region By Embedded Micro Thin Film Thermocouples. *Journal of Manufacturing Processes* 13(2):147–152.
[285] Werschmoeller D, Li X, Ehmann K (2012) Measurement of Transient Tool-Internal Temperature Fields During Hard Turning by Insert-Embedded Thin Film Sensors. *Journal of Manufacturing Science and Engineering* 134(6):021007.
[286] Wolf T, Iovkov I, Biermann D (2021) Influence of a Discontinuous Process Strategy on Microstructure and Microhardness in Drilling Inconel 718. *Journal of Manufacturing and Materials Processing* 5(2):43.
[287] Wu J, Zhang L, Chen T (2009) Model Predictive Control For Networked Control Systems. *International Journal of Robust and Nonlinear Control* 19(9):1016–1035.
[288] Xie Z, Li J, Lu Y (2018) An Integrated Wireless Vibration Sensing Tool Holder For Milling Tool Condition Monitoring. *The International Journal of Advanced Manufacturing Technology* 95(5-8):2885–2896.
[289] Xie Z, Lu Y, Li J (2017) Development And Testing Of An Integrated Smart Tool Holder For Four-Component Cutting Force Measurement. *Mechanical Systems and Signal Processing* 93:225–240.
[290] Yagi M, Sawada Y (2014) State Estimation for Networked System with Random Delay Using Kalman Filter. *Stochastic Systems Theory and its Applications (SSS)* 2014:9–14.
[291] Yaldız S, Ünsaçar F (2006) A Dynamometer Design For Measurement The Cutting Forces On Turning. *Measurement* 39(1):80–89.
[292] Yamamoto T, Matsuda R, Shindou M, Hirogaki T, Aoyama E (2021) Monitoring of Vibrations in Free-Form Surface Processing Using Ball Nose End Mill Tools with Wireless Tool Holder Systems. *International Journal of Automation Technology* 15 (3):335–342.
[293] Yao X, Zhou J, Lin Y, Li Y, Yu H, Liu Y (2019) Smart Manufacturing Based On Cyber-Physical Systems And Beyond. *Journal of Intelligent Manufacturing* 30 (8):2805–2817.
[294] Yao Y, Pan Y, Liu S (2020) Power Ultrasound And Its Applications: A State-Of-The-Art Review. *Ultrasonics Sonochemistry* 62(2020):104722.
[295] Yi L, Gutzeit K, Ehmsen S, Kölsch P, Glatt M, Aurich JC (2021) Exploration Of The Potential Of Polymer 4D Printing: Experiments On The Printing Quality And The Impact Of Temperature And Geometry On The Shape-Changing Effect. *Procedia CIRP* 103:103–108.
[296] Yoshioka H, Kojima K, Toyota D (2020) Micro Patterning On Curved Surface With A Fast Tool Servo System For Micro Milling Process. *CIRP Annals* 69(1):325–328.
[297] Zeng QY, Zheng XF, Zhang GH, Chen Le (2011) Development of Cutting Tools with Built-in Thin Film Thermocouple for Monitoring Machining Temperature. *Advanced Materials Research* : 189–193. 3170–4.
[298] Zhao Y, Zhao Y, Wang C, Liang S, Cheng R, Qin Y, Wang P, Li Y, Li X, Hu T (2016) Design And Development Of A Cutting Force Sensor Based On Semi-Conductive Strain Gauge. *Sensors and Actuators A: Physical* 237:119–127.
[299] Zheng L, Chen W, Huo D (2020) Review of Vibration Devices For Vibration-Assisted Machining. *International Journal of Advanced Manufacturing Technology* 108(5-6):1631–1651.
[300] Zhou C, Guo K, Sun J (2021) An Integrated Wireless Vibration Sensing Tool Holder for Milling Tool Condition Monitoring With Singularity Analysis. *Measurement* 174:109038.
[301] Zoppi S, van Bemten A, Gursu HM, Vilgelm M, Guck J, Kellerer W (2018) Achieving Hybrid Wired/Wireless Industrial Networks With WDetServ: Reliability-Based Scheduling for Delay Guarantees. *IEEE Transactions on Industrial Informatics* 14(5):2307–2319.