CHAPTER EIGHTEEN

Sensor-Assisted Machining

Contents

18.1 SENSORS AND SYSTEM ARCHITECTURE

It is well known that steadily increasing demands for higher accuracy and productivity lead to the implementation of large-scale process automation and, consequently, towards fully automated and unattended flexible manufacturing systems. Such wide range of process automation is attempted in the face of variations in the manufacturing environment, including work material, tooling, machinery performance, rates of production, order of process elements, etc. In classical manufacturing, a large number of these processes are machining based, involving various cutting operations. To ensure the optimum performance of such complex systems, different sensors are needed for in-process monitoring and feedback for controllers. As shown in Fig. 18.1, the focus of monitoring is on the machine tool (diagnostics and performance monitoring), the cutting tools or tooling (state of wear, lubrication, alignment), the workpiece (geometry and dimensions, surface features and roughness, tolerances, metallurgical damage), or the process itself (chip formation, temperatures, energy consumption).

All of the above-mentioned four focus areas are subject to monitoring needs, often with competing requirements for time response or location of sensors. However, in order to establish the states of the individual elements of machining systems, a multiple-sensor system is necessary for process monitoring, as illustrated in Fig. 18.2. The machining process is continuously monitored by different external sensors to quantify process performance or provide relevant information for process optimization in on-line mode using sensors. Besides the detection of process deviations, the thresholds for process variables are also established to produce an automatic feedback of the machine tool by changing the process parameters. This approach is of special

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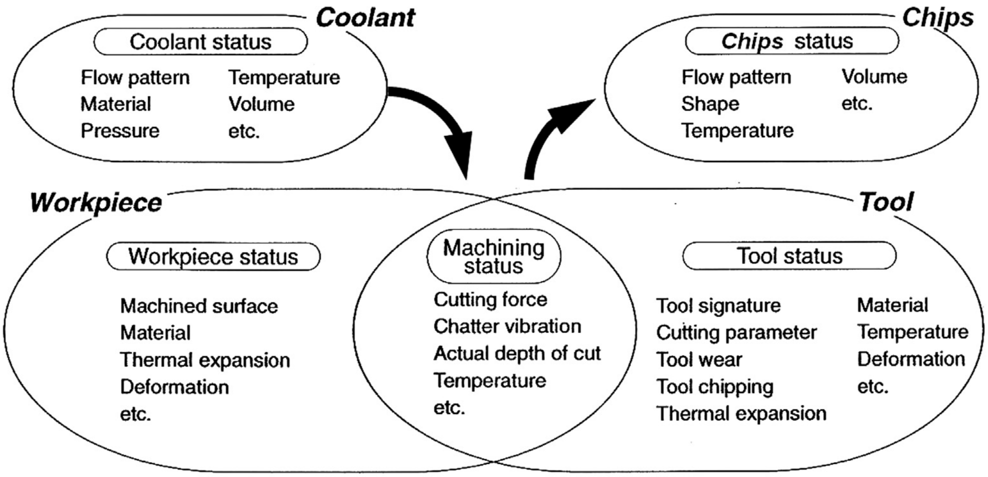

Figure 18.1 Sensing objective during cutting [1].

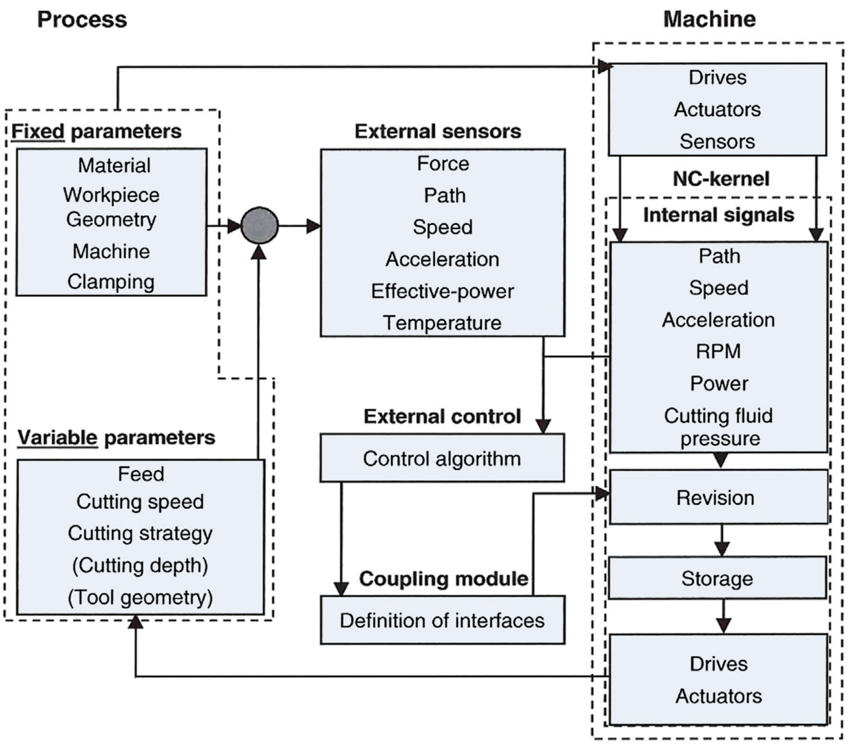

Figure 18.2 A scheme of a multiple-sensor drive machining process control system [2].

importance for monitoring processes that are categorized as precision manufacturing, i.e., for which the tolerances on form, dimension or surface features are very tight [3]. Precision machining processes are characterized by very small material removal rates, very low process power consumption, and the special requirements that the sensor does not intrude in the process or require substantial modification of the machine. Because the most important element of the sensor system is the signal processing methodology for feature extraction and decision-making, an intelligent (knowledge-based) monitoring system can be implemented [1–4]. This monitoring system is capable of extracting multifaceted information about the machining environment and performing simultaneous multiphenomena sensing. The currently available sensors for machining environment monitoring are mostly designed for observing a single phenomenon, such as static or dynamic components of the resultant cutting force or acoustic emission (AE) signals using direct or indirect measurement methods [5]. As a result, they do not integrate the advantages, such as compactness, multifunctionality, ease of use, etc. Advanced sensor design, coupled with signal processing technique, permits improved information about the process condition, enabling process optimization and control. The desirable performance features of in-process sensors can be listed as follows [1]:

- Simultaneous multiphenomena sensing functions to extract multifaceted information, enabling a total understanding of the manufacturing environment.
- High response and sensitivity to extract small signals from the status of the monitored object under the influence of various disturbances arising during machining.
- Compact sensor structure to mount the sensor device near the machining point and extract the necessary information for precise recognition of the machining status.
- Resistance and stability against outer disturbances.
- Easy to use and maintenance free.

Fig. 18.3, after Hoshi [3,6], shows the results of a survey of different monitoring methods for a variety of machining operations. This survey covered the following measurements or sensors for edge chipping, fracture and wear related to cutting tools, and poor hole quality obtained by drilling: touch sensors, load amperage, vibration, torque/force limiter and AE. The bulk of the processes monitored are drilling and the most frequently used approaches of monitoring are tool touch (with 100% success) and load amperage (80% success). Vibration sensing and AE are the next most often applied, to be 75% and 33% successful, respectively.

New demands were placed on sensors and monitoring systems for advanced machining technologies, such as high-speed machining or hard machining, which allow the production of precision components. They include the following challenges [7]: low cutting energy when very small layer is removed from the workpiece, response time in milli- or submillisecond ranges for extremely high spindle speeds

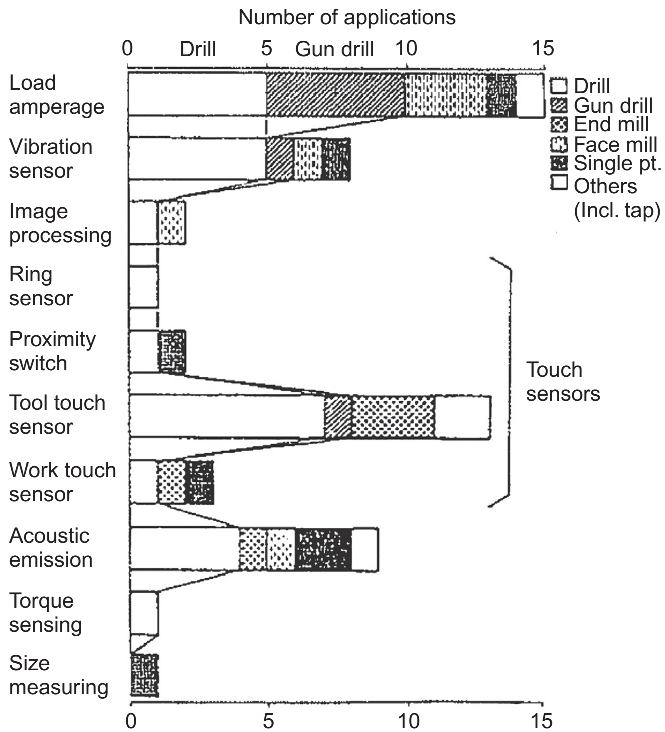

Figure 18.3 Monitoring methods in manufacturing [6].

approaching 100,000 rpm, difficulties in the installation of sensors in complicated tooling systems, protection against high energy produced by moving pieces in case of tooling failure, producing additional noise to sensor signal due to dynamic effects of tool entry and exit, additional noise produced by minimum quantity lubrication (MQL) system, and difficulty with failure sensing for coated tools in dry machining. In particular, some in-process sensors for precision or ultra-precision machining shown in Fig. 18.4A can be capable of improving the process control over critical process variables, which leads to tightening control limits and increasing productivity. As a rule, if the percentage change of the feature of the tool or workpiece being monitored decreases, the reduction of the effective signal for monitoring follows. For instance, the signal-to-noise ratio is reduced due to machining with very small uncut chip thickness, as shown in Fig. 18.4B. Moreover, Fig. 18.4B illustrates the suitability of three sensors (force, acceleration and AE) for monitoring of high-speed machining with decreasing chip thickness value.

Examples of some most frequently used sensors (AE, vibration, power and displacement) along with their integration with machine tool or CNC control system are shown in Figs 18.5–18.7. In particular, piezoelectric sensors (shown in Fig. 18.5)

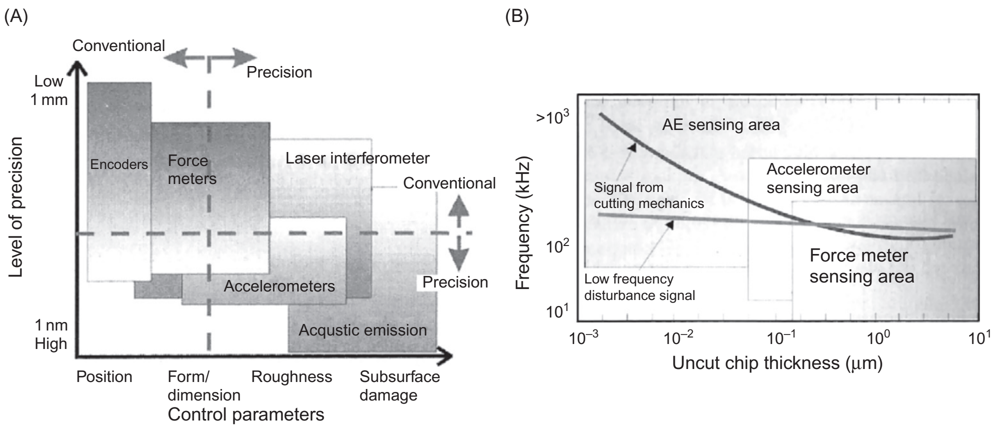

Figure 18.4 Sensor application versus level of precision and error control parameters (A) and the influence of noise on the effective signal in monitoring HSM (B) [7].

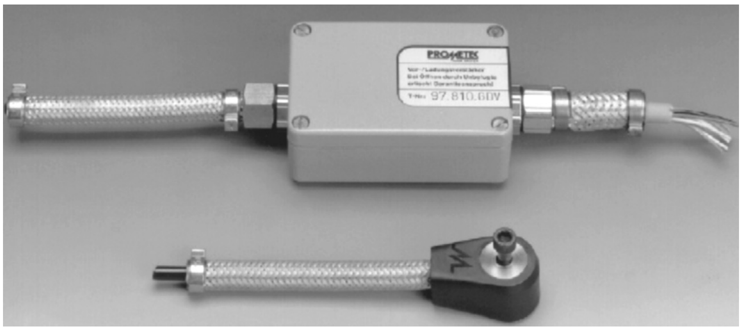

Figure 18.5 Ultra-sound and vibration piezoceramic AE sensor AE 30, Type S; preamplifier KSV [8].

can be used for numerous applications, including force, power, strain, pressure, vibration and AE measurements. They are highly sensitive, inherently stable, reliable, rugged and have wide frequency response, uniquely wide dynamic range, small size and practically unlimited life. Typically, sensors are mounted on the turret head housing and the tool post in turning, on the spindle head in milling, on the spindle quill in drilling and fitted on the headstock or dresser unit in grinding [4,10]. The sound sensor from Fig. 18.6C can also be mounted directly on the end of the spindle of a grinding machine with wireless signal transmission. It should be noted that the location of the sensing transducer of an AE sensor can influence the magnitude of the signal detected. In general, the amplitude decreases as distance from the cutting point increases and is sharply attenuated by passing through a contact surface.

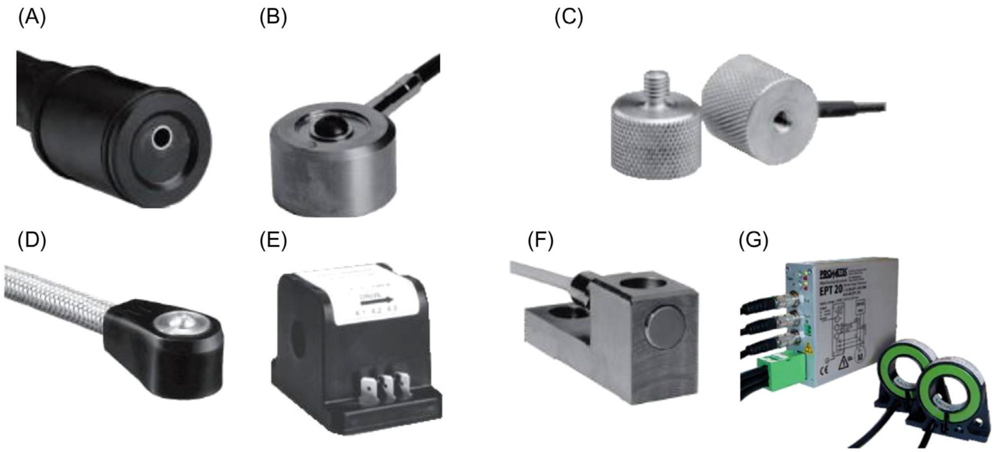

Figure 18.6 A range of sensors used for monitoring metal cutting and grinding operations: (A) Fluid sound sensor for structure-borne sound and acoustic emission (AE) via coolant flow from workpiece. (B) Wideband sensor for structure-borne sound and AE. (C) Wireless sensor for structure-borne sound and AE (1 — sensor and transmitter, 2 — receiver). (D) AE and vibration sensor. (E) Hall current sensor for effective power. (F) Inductive displacement sensor for force and elongation. (G) Power transducer [8].

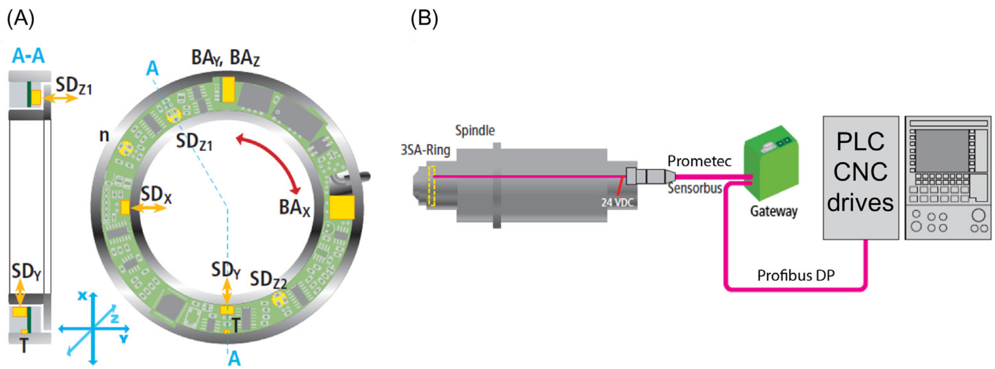

Figure 18.7 Construction of three-axis measuring ring for forces (A) Integrated with direct spindle and connected with CNC control system (B) [9].

The measuring ring (3SA-Ring) shown in Fig. 18.7A is capable of measuring ten spindle features with nine sensors, as follows:

- 3D shaft displacement (SD) at 2 μm resolution with four inductive displacement sensors.
- 3D bearing acceleration, one radial up to 10 kHz with ICP output signal, one radial, one axial up to 1 kHz.
- Shaft speed sensor (n), one impulse/revolution.

- One temperature sensor (T).
- Counts time when spindle-on-power.
- Counts time when spindle-on-speed.

Its integration with CNC control system is shown in Fig. 18.7B. In particular, CNC/PLC reads the values and/or the signals from the measuring ring and spindle-tool position can be corrected [10].

Vibration, sound, ultrasonic vibration and AE are actually all vibration measurements, although the frequency range differs in each of these monitoring methods and, in addition, sound is airborne vibration when all others are mechanical vibrations of the machine structure. The frequency range in vibration measurements is typically from about 1 Hz to about 10 kHz (16 kHz or even 20 kHz is used as a limit). In sound measurements, the frequency range is from 20 Hz to 20 kHz, and in ultrasonic vibration the frequency ranges from 20 to about 80 kHz. On the other hand, AE starts where ultrasonic vibration ends up and ranges to about 1 MHz [11]. The vibration signals (often together with passive force) were found to be very effective for monitoring drill wear and breakage for a wide range of drill sizes. However, a higher frequency range from 0.5 to 40 kHz is more suitable for very thin drills (for drills of 1 mm diameter, the natural frequency is about 25 kHz). AE is a phenomenon that occurs when, for different reasons, a small surface displacement of a material surface is produced. AE sensors are used for the tool wear and failure detection occurring in various metal cutting processes, but the appropriate frequency ranges are different. For example, the 200 kHz sensor is suitable for tool wear monitoring, whereas the 800 kHz sensor can be used for tool-breakage detection [11].

The tool monitoring system (TMS) shown in Fig. 18.8A reliably monitors machining operations, such as turning, drilling, milling, sinking, reaming, thread cutting, broaching, etc., and also offers, depending on the configuration, the following functions:

- Rapid detection of machine collisions.
- Detection of random tool breakage.
- Prevention of tool breakage from overload.
- Wear detection.
- Tool contact/workpiece contact.
- Process visualization and optimization.

The monitoring system from Fig. 18.8 consists of four modules, namely:

- Sensors that record the loads subjected to the tool during processing and send the appropriate signals to the monitor module.
- Monitor modules that process the sensor signals, compare the current signal with the set limits or with the learned limit values and generate information for the machine operator or the controller.
- Machine interface modules which are the interface between monitor modules and the machine controllers.

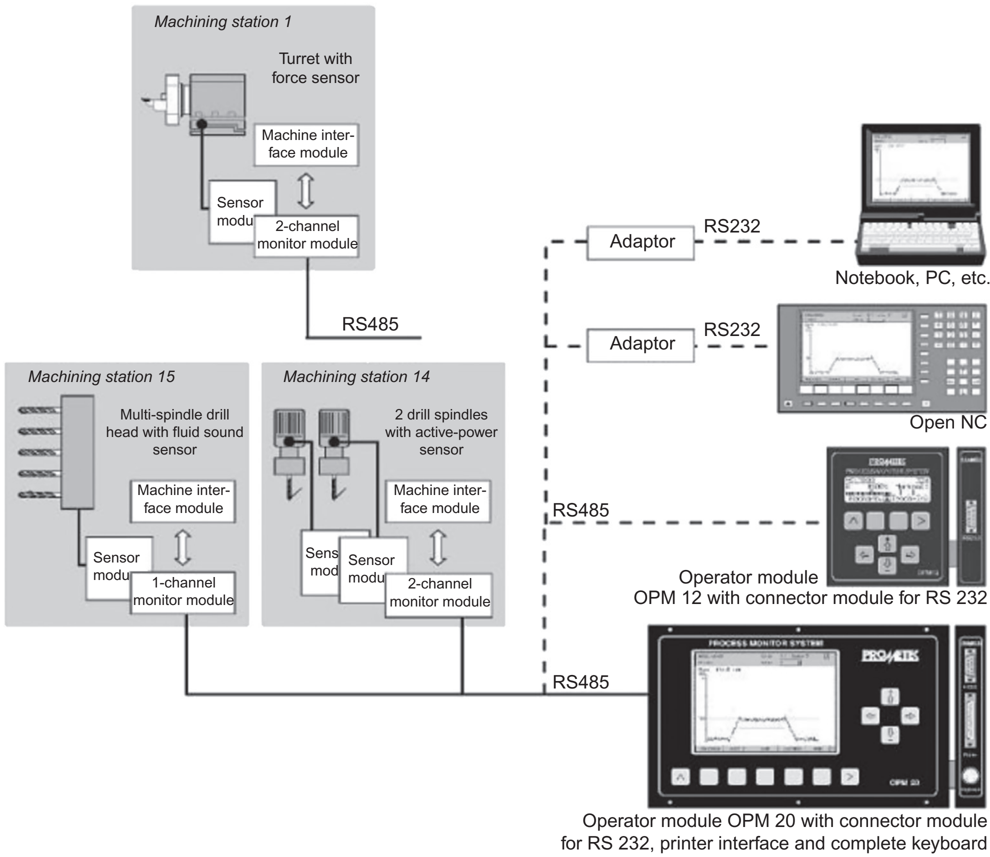

Figure 18.8 Architecture of a modular process monitoring system PROMOS 2 [8]. *From PROMETEC GmbH.*

- The operator panel module or the operating and visualization software in an open NC control, giving fast and direct access to all of the parameters and settings in the monitoring system.

In multiple-sensor monitoring systems the fundamental problem is to determine the significant information for particular feature recognition. The raw signals obtained from the AE, force and current sensors must be processed to provide useful information on the cutting state because their interpretation is very difficult due to the randomness of the recorded signals. In the time domain, the signal feature can be represented by a number of statistical parameters, such as the root mean square (RMS) value, arithmetic mean, standard deviation and kurtosis, as well as other statistical characteristics of the signal distribution. On the other hand, in the frequency domain, fast Fourier transform (FFT) is the most frequently used signal analysis technique (rarely is Wavelet Transform used). A number of FFT-based functions, such as power spectrum, autocorrelation, cepstrum and also two-channel functions including cross-correlation, cross-spectrum, frequency response as well as some multisignal frequency response function with more than two channels [3,4,11]. Wavelet transform (also together with artificial neural networks (ANNs)) is described as a good solution in the time−frequency domain, and both continuous and discrete wavelet transforms are used for tool-breakage detection using spindle and feed current signals. In particular, it may be a perfect tool for many applications requiring automated monitoring of manufacturing operations, i.e., micro-drilling operations due to obtaining signals without high-frequency components.

There are many approaches to sensor data fusion and decision-making, but besides the linear discriminant function, one effective technique is the use of neural networks [11−14]. When using multiple-sensor systems, the information provided by the process models (e.g., force-, AE- and temperature-based models) should be synthesized in order to determine the best estimates for the process variables. It was documented in [13] that a complex network with two hidden layers provides the lowest mean square error for the wear estimate in comparison with estimates based on the outputs from different sensors and a simple network with one hidden layer. Fig. 18.9 shows the scheme of the operation of a tool condition monitoring (TCM) based on sensor fusion with a complex three-layered neural network. The system employs multiple sensors, i.e., AE, piezo-quartz force and electro-magnetic current sensors. Inputs to the sensing system include features of the AE signal (autoregressive (AR) parameters and amplitude of energy within certain predefined frequency bands), cutting force (amplitude of energy within certain predefined frequency bands) and average motor current. The data—time based and frequency based—is sampled and analysed in real time. The signals from the sensors used are processed using a multichannel AR series model or FFT technique. The resulting AR coefficient matrices or power spectral density are passed to the feature extraction block, in which the features that are most sensitive to tool wear are selected. Then, the six most significant features are fed into a previously trained ANN to generate final decision on the state of the cutting tool. As a result of this signal processing procedure, up to 97% reliability was achieved in correctly identifying the wear state of the tool during single-point turning of carbon steel [3].

In case of CNC machine tools, the measured sensor signals are processed by real-time monitoring and control algorithms, and the corrective actions are taken accordingly by the CNC control system (see Fig. 18.2). The corrective actions may consider change of spindle speed, feed, tool offsets, compensation of machine tool positions, feed stop and tool change, depending on the process monitoring and control application. Such a sensor-assisted cutting is called *intelligent machining* and the appropriate monitoring system is called *intelligent monitoring system* (IMS) [15]. Its basic feature is

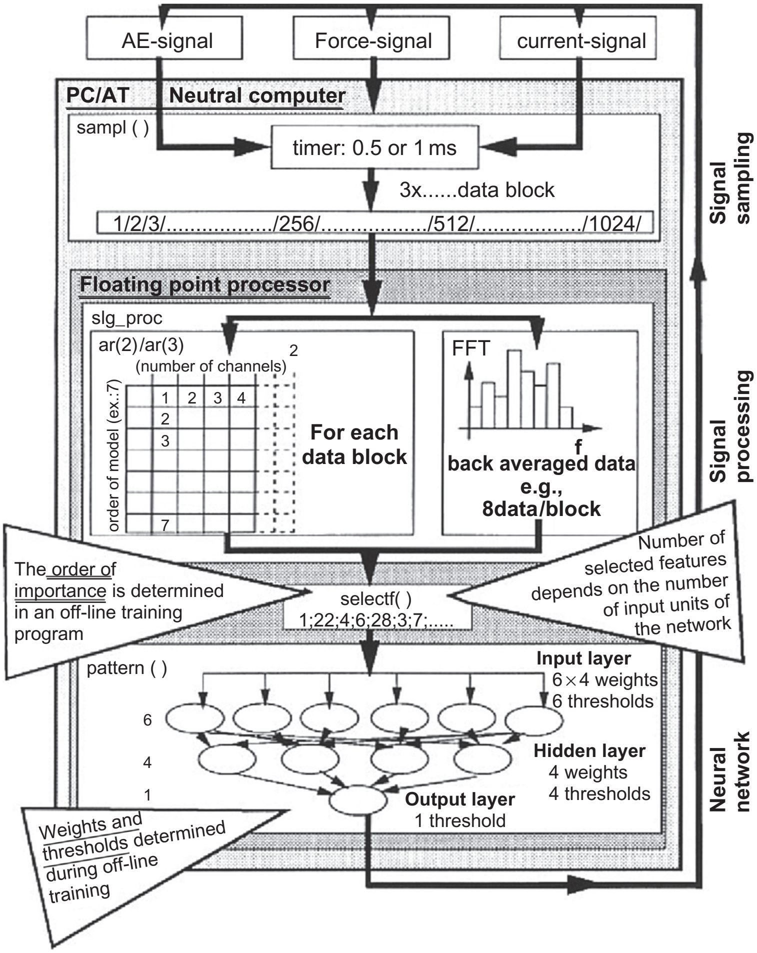

Figure 18.9 Schematic of operation of the monitoring system [12].

that the CNC control system must open to allow integration of a user-developed real-time application programme. From the definition, the intelligent system should be able to automatically perform the following tasks [16]:

- Test and select the best configuration of sensors and signal processing methods, and, as a result, select measured signal feature that indicates the best correlation with the monitored phenomenon.
- Automatically model a relationship between the extracted feature and the relevant phenomenon without human interaction due to self-learning abilities.
- Represent the acquired knowledge in a human comprehensive form.

A concept of the structure of an IMS is shown in Fig. 18.10, which shows that the software module includes three steps in assessing the final state of the monitored

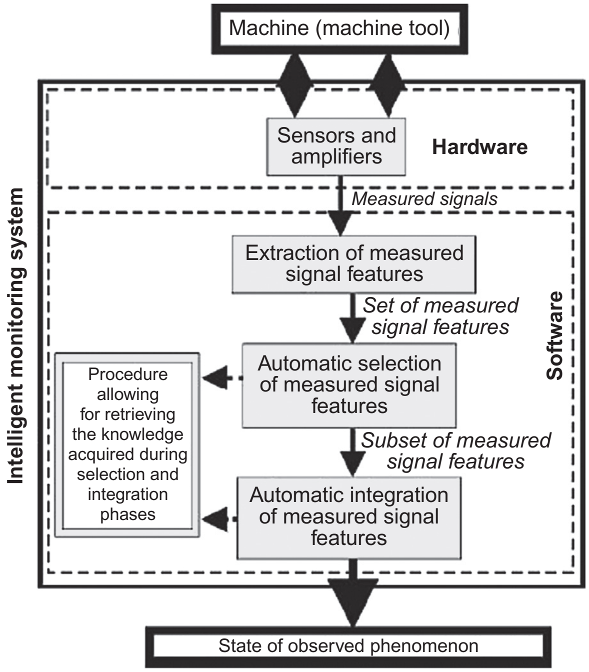

Figure 18.10 Block diagram of an intelligent monitoring system (IMS) [16].

phenomenon. In the first, feature-extraction step, several features of the measured signals are estimated and, further, the machine tool operator selects the most important feature based on personal experience (the feature-selection step). Finally, the previously selected features are integrated within a decision-making procedure (feature-integration step).

Another way to implement the IMS is developing new hardware/software systems in order to shift the human-machine tool operator position to a higher level of supervision. The first approach postulates the implementation of an intelligent monitoring system designer that consists of several modules with the same functions as IMS from Fig. 18.10, but employing advanced processing methods and algorithms (e.g., Feed Forwad Back Propagation (FFBP) neural networks, genetic algorithms, neuro-fuzzy logic systems). In particular, such a system reduces the time required for final decision regarding the state of the monitored object or phenomenon. The second approach is based on the implementation of the intelligent tool (IT), which is a software/hardware system acting in a defined environment (machine tool, workpiece) and automatically enabling assessment of its current condition, prediction of its state in the near future, and assessment of the state of other phenomena based on the information available in the considered environment [16].

18.2 PRACTICAL EXAMPLES OF MONITORING SYSTEMS FOR METAL CUTTING APPLICATIONS

The machining process has always required supervision, and in the past this function has usually been the responsibility of the machine tool operator. However, with the increasing use of automated manufacturing systems, ending with fully unmanned systems, there is a visibly growing need for systems that can automatically monitor the machining or other manufacturing processes involved. Continuous in-process monitoring is the key to zero-defect production in the automated factory of the future. At present, sensor-based monitoring of machining operations includes TCM, unmanned machining, process control and, advanced tasks such as innovative signal processing, sensor fusion and other relative applications [5]. In fact, numerous different sensors are available for various monitoring aspects of the machining and machining environments, as proposed in Fig. 18.11.

For cutting tools these systems are termed *TMS* or *TCM* systems. The main goal in the use of sensor systems for TCM in machining and grinding is to enhance productivity, and hence increase competitiveness by maximizing tool life, minimizing machine downtime, reducing scrappage and preventing damage [17]. Commercially

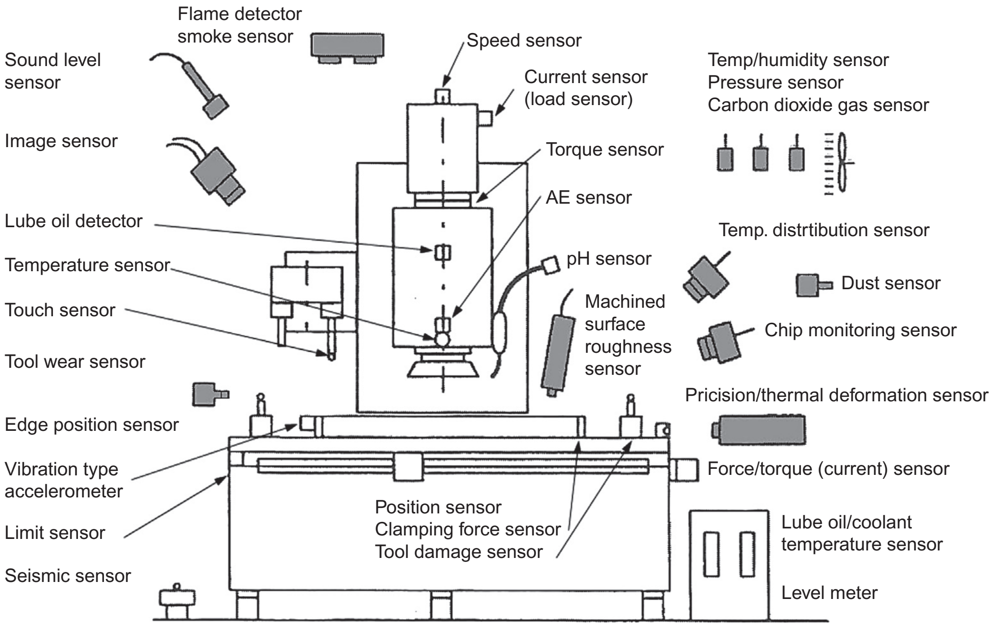

Figure 18.11 Possible sensors used for monitoring of highly sophisticated machine tool after Moriwaki [2].

available TCM systems are used to detect tool breakage, collision, wear and missing tool and states for machine tools. Other sensors which can be used for machining process monitoring depending on the automation level and particular production demands, as shown in Fig. 18.11.

Fig. 18.12A illustrates the structure of a TMS that can be used to monitor turning processes on CNC lathes, and drilling and milling processes on machining centres. This system utilizes a strain gauge sensor mounted in the tool-holder (a) to measure torque, and axial and radial forces. For effective process monitoring, it is important that the signal used should vary progressively as the tool wears, and not just at the point when it breaks. It is well known that during a drilling operation, the axial force component provides a better indication of the cutting edge's condition as a function of wear rather than the torque value. This differential allows more accurate setting of realistic alarm levels. Electronics embedded into the tool-holder include a preprocessing unit and A/D converter. Sensor signals (electrical signals) are transmitted to the signal-processing device (single- or multi-channel monitoring unit) by means of a wireless signal transmission unit consisting of the ring (b) and the head (c). Once the signal is received, the processing device can immediately initiate action by the machine controller if the tool is worn, broken or air-cut occurs. Fig. 18.12B shows how continuous monitoring of the axial force can be used to trigger four alarm levels:

- Level I can be used to detect progression in the tool wear. The alarm signal can be used to initiate a tool change after completion of the cutting operation.

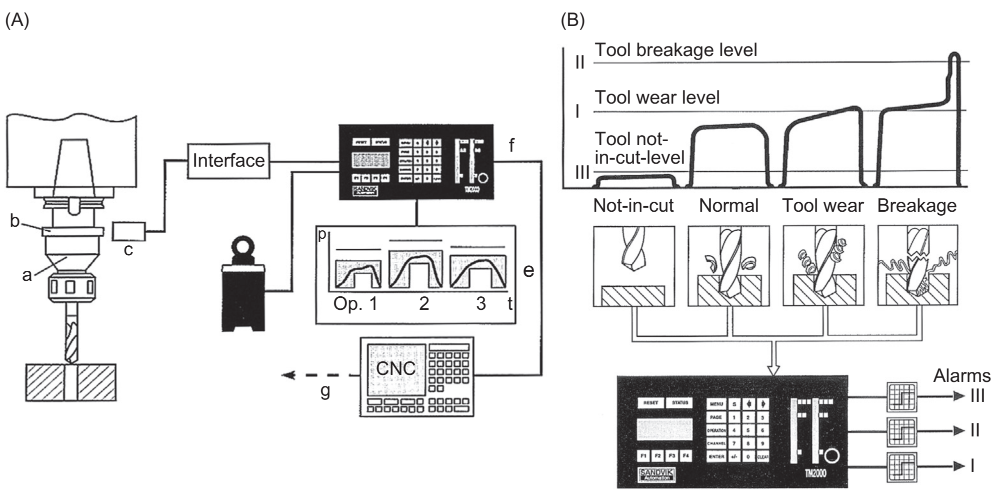

Figure 18.12 Drilling process monitoring using sensors for torque and force measurements within the tool holder and current sensor [18,19]: (A) Structure of monitoring system. (B) Monitoring strategy.

- Level II can be utilized for tool breakage/catastrophic wear. This signal should be used to stop the machine immediately when the breakage occurs.
- Level III is planned for detection whether the tool is in-cut or not-in-cut. This may indicate that either the tool or the component is missing.
- Level IV can be used for crash protection. Like level II, this alarm signal should stop the machine immediately and, as a result, protect the machine tool against damage.

Fig. 18.13 schematically depicts the methods by which the signals from piezoelectric sensors are evaluated by a monitoring system for tool breakage, and tool wear and unpredictable collisions in the working area. In the case of turning, shown in

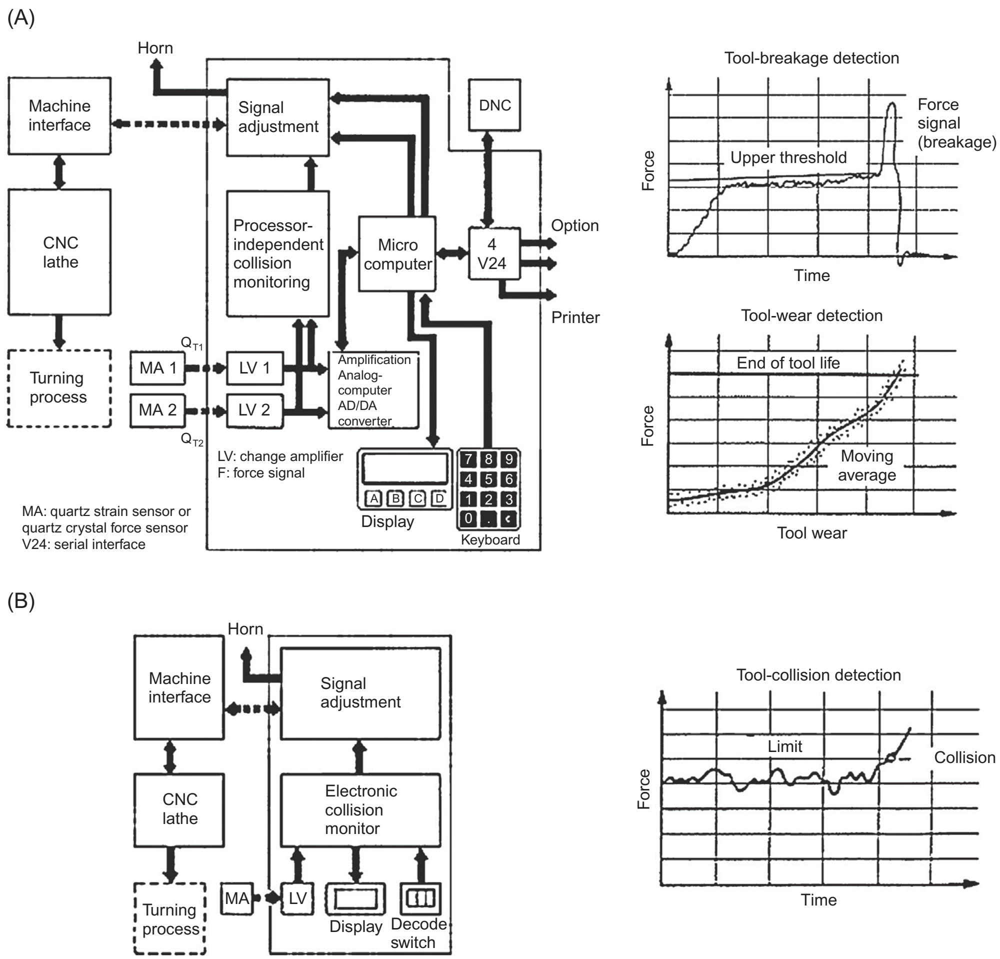

Figure 18.13 Tool-condition monitoring systems [18]: (A) The tool-breakage and tool-wear detection system. (B) The collision-monitoring system.

Fig. 18.13A, piezoelectric strain sensors are attached to specific points on the turret housing of the turning centre in such a way that they produce strong signals on the cutting action. At the moment of tool breakage, there is a significant rise in the cutting force, followed by a sharp drop, as illustrated in Fig. 18.13A. This pattern is a tell-tale sign of tool breakage and forms the basis on which the system works. The digital breakage-monitoring system continuously monitors the upper and lower force values and if these values deviate from the norm because of the breakage, a command is issued to stop the feed motor. As a result, this action prevents any continued operation with a damaged tool.

The tool wear monitor is also a digital system based on the rise in the force level that occurs over the lifetime of the cutting edge and operates by checking the rise against the force differential measured on a reference cutting edge operated until blunt. The wear threshold (end of tool life in Fig. 18.13A) is obtained by adding the initial force value of a new cutting edge to the force differential of the reference tool. Once this limit is exceeded, the system indicates that the tool is worn and should be replaced.

A schematic diagram of typical circuitry and a graph of the expected force change during a collision are shown in Fig. 18.13B. The operating principle applying to a turning centre is that the strain transducer measures the deformation in the turret during machining and then compares it with a preset threshold value. If the measurement exceeds the threshold, a command is given within milliseconds to stop the feed motor in order to avoid damage to the machine or workpiece.

One of typical applications of the AE sensors in tool-condition monitoring performed on a machining centre is shown in Fig. 18.14A. It should be noted there that the AE waves travel through the cutter, spindle and concrete, rather than through the workpiece, etc. The AE signal is picked up by a piezoelectric strain transducer fitted at some convenient position on the turning-centre turret housing. By using a pulsor, an artificial signal can be generated that simulates the vibrations associated with a tool breakage. The pulsor enables the operator to localize the AE sensor accurately in the optimum position and the amplifier gain to be adjusted for maximum sensitivity of the monitoring system. This procedure means that tool breakage is reliably detected, since the signal will be at the same level as the simulated breakage signal transmitted from the pulsor. The tool monitor continuously recognizes the current state of the tool during the relevant part of the CNC programme. If the tool fails, the alarm is instantly activated, and if any tool disturbance is detected, then cutting action stops immediately. Fig. 18.14B presents a measurement circuit for the acquisition of AE-signals in machining process. The AE signal generated by the AE sensor has low energy content and the signal-to-noise ratio is thus low, making disturbance-free signal transmission more possible. Due to this fact, the raw signal is preamplified and then filtered correspondingly to the frequency range and the particular monitoring

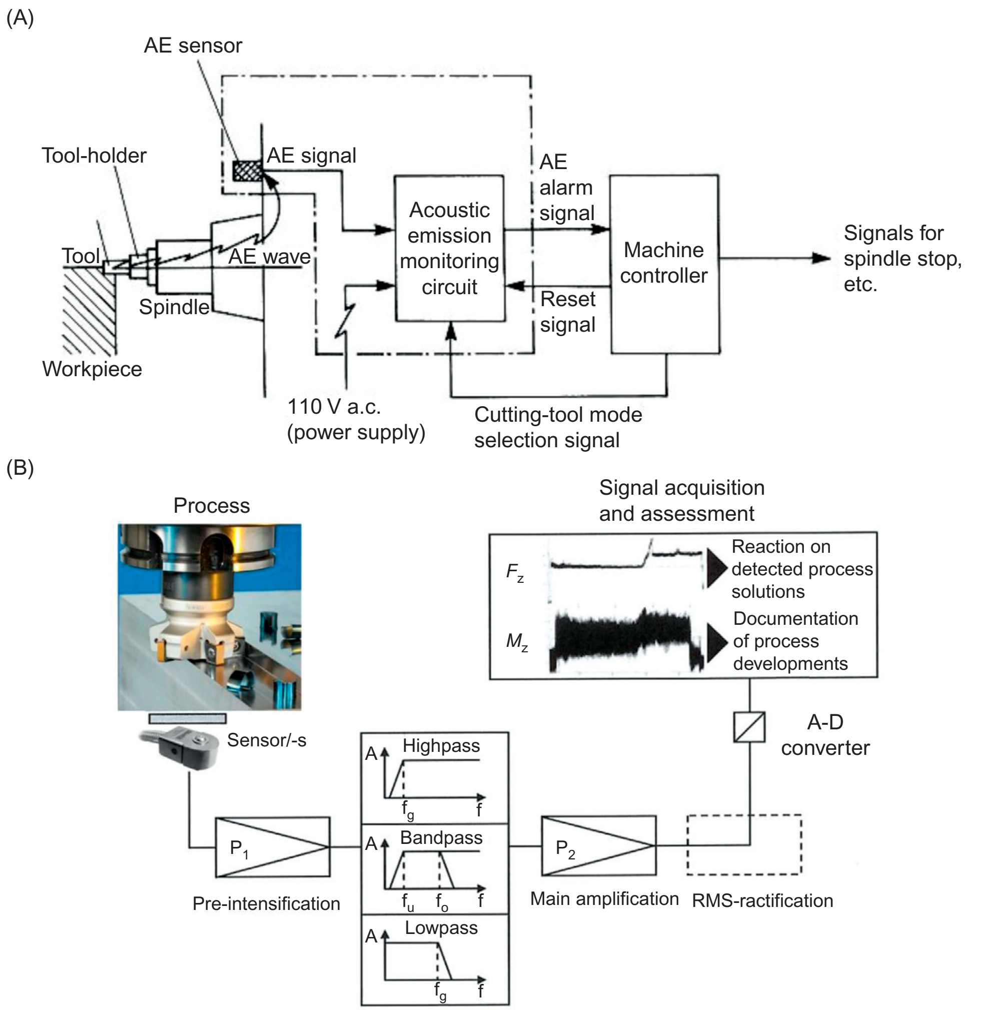

Figure 18.14 Typical application of the acoustic emission (AE) principle for tool-condition monitoring: (A) A machining-centre application of AE [18]. (B) A scheme of AE-signal processing and acquisition [2,5].

task. Taking the latter fact into consideration, either high-pass or band-pass filtering of the sensor signals is performed. After filtering, the signal is amplified in the main amplifier and finally the effective value of the sensor signal (the RMS value) is formed [3].

The monitoring system for collision detection collision monitoring system (CMS) using a one- or two-channel control panel during the event of CNC programme is overviewed in Fig. 18.15A. The CMS can be suitable for a range of CNC machine tools, including CNC lathes, machining centres, and drilling, broaching, turn-broaching and grinding machines using several different sensors, such as magnetic

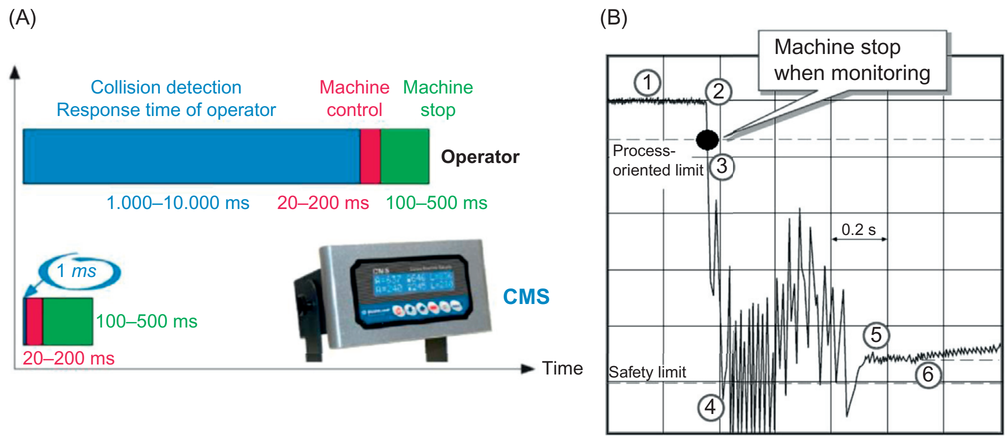

Figure 18.15 Collision monitoring system (CMS) for machine tools [20]: (A) Control panel and comparison of reaction times. (B) Collision detection. 1 – rapid traverse motion, 2 – first contact of tool and workpiece, 3 – abrupt increase in processing force, 4 – NC programme starts, five-spindle jammed when main spindle motor is overloaded, 6 – motor current is switched off by fuse.

inductive sensors, piezoelectric force and strain sensors, and AE sensors with an amplifier. The monitor display shows the actual and maximum force values and the switch-off limit. The rapid traverse is stopped just after the first contact of the tool and the workpiece (point 2 in Fig. 18.15B), resulting in a sudden increase in the measured strains (force), as in the previously discussed case shown in Fig. 18.13B. This resulted in spindle jamming and overloading the main spindle motor. After several tens of seconds, the CNC programme reacts by switching off motor current via a fuse due to crossing the safety limit adjusted.

Hard turning, which is often used in the manufacturing industry as an economic alternative to grinding, belongs to the class of machining processes with unpredictable reliability [21]. As a result, conventional wear-monitoring systems are not suitable for finishing hard turning operations due to a conglomeration of phenomena, such as chip formation, tool wear and surface finish, which exhibit unique process behaviour. It is proposed to monitor flank and crater wear during hard turning by means of a force-based monitoring system supported by a dynamic artificial intelligence technique (dynamic neural networks). In addition, a self-organizing map analysis, also known as Kohonen maps, was applied to determine possible correlations between process variables and remove occurring disturbances from the force signals [21].

A real problem arising in precision hard turning is the compensation of dimensional errors induced by tool wear and thermal expansion of both cutting tool and workpiece. Typically, thermally induced errors are compensated by a precalibrated error compensation method, whereas tool wear induced error is suitable to be

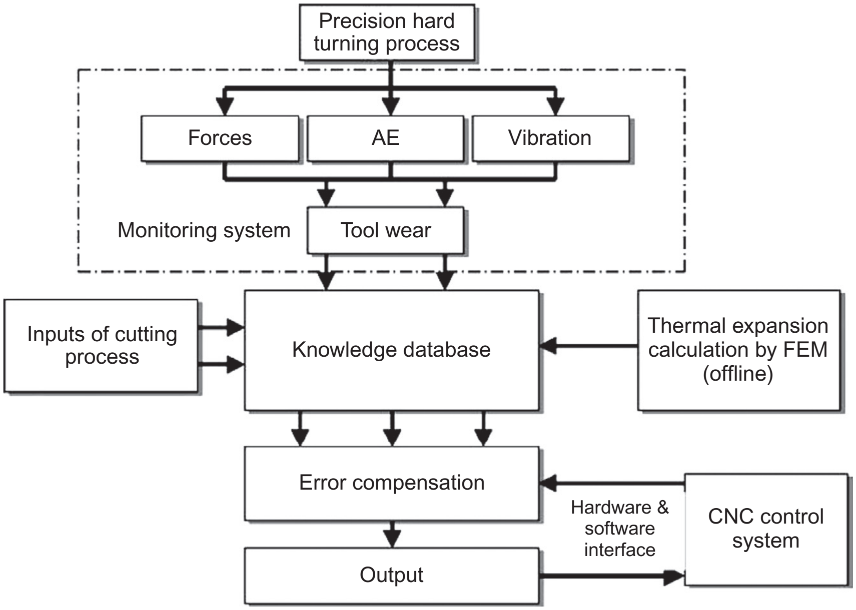

Figure 18.16 Method of dimensional error compensation in precision hard turning [6].

compensated with active error compensation. An integration of these two compensation methods in one system, linking with a CNC control system, is shown in Fig. 18.16. A tool wear-monitoring system was installed to identify the relationship between tool wear and sensor signals, and corresponding thermal expansions of the tool and workpiece were predicted by finite element modelling computation. As a result, a new NC code was generated and transferred to the CNC control system through the interface between the monitoring and CNC control systems.

The highest hierarchical level of manufacturing systems is *intelligent manufacturing*, also termed *sensor-based intelligent manufacturing* [15,22]. It is capable of performing not only the requirements of ordinary manufacturing systems but also makes manufacturing in alien worlds, such as in the atomic-scale world (nanotechnology) or even in space. In addition, intelligent manufacturing enables creation of self-evolving manufacturing systems that use automatic data collection and self-learning, and supports the development of creativity by allowing unskilled designers to manufacture complex parts easily. The required knowledge is basically composed of knowledge about manufacturing phenomena (physical process model) and knowledge about available manufacturing processes. The fundamental structure of the sensor-based intelligent manufacturing system is shown in Fig. 18.17. The main components of the system are knowledge, sensors and actuators. From the phenomena occurring in manufacturing/machining, the dominant physical quantities are extracted by sensors

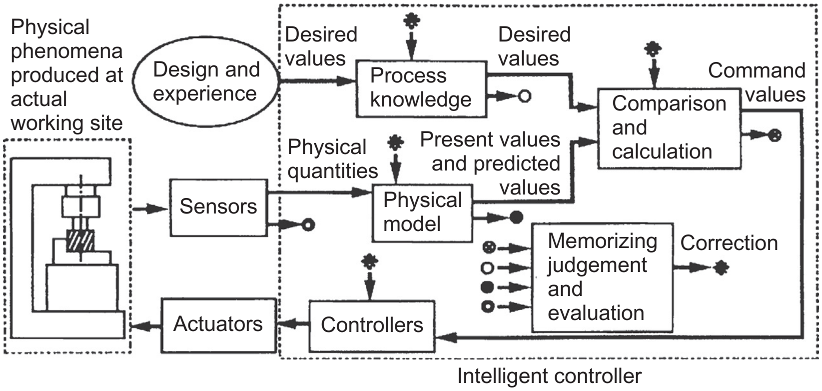

Figure 18.17 Fundamental structure of the sensor-based intelligent manufacturing system [22].

and inserted as an input to the physical model. As a result, the current state of the process is identified and its future state can be predicted. The present and predicted values are compared with the desired values provided from the design system. Any discrepancies between these values cause appropriate modifications of the process parameters. and the required motions of the actuators are calculated and sent as command values to controllers. Moreover, all activities described are memorized, judged and evaluated by a separate monitoring function. The control algorithms for each function are modified, enabling the self-evolution of the manufacturing system.

A structure of an intelligent machining centre, which was designed and constructed using the conceptual methodology described above, is illustrated in Fig. 18.18. In the intelligent machining centre, four main functions are essential, namely: detection of deformation, calculation of compensation values, implementation of compensation and counter-measurements. This machining centre implements the functions of compensating thermal distortion by thermal actuation, intelligent machining by force/torque control, fail-safe operation by using hydraulic coupling, and external control not only by a conventional NC controller but also by workstations, connected through the internet or artificial satellite. The spindle itself has the ability to measure the force and torque within the selected rates and fail-safe performance to protect the system against excessive torque. The protection of the head, the table and the saddle against the effects of abnormal loads was achieved by fitting a one-directional force sensor and a fail-safe element to them. Deformation sensors were coupled to the surfaces of the column and the head to measure the mechanically and thermally induced deformations of the machine tool structure. Moreover, several temperature sensors are put onto the surfaces to detect their local temperatures and heating by the environment. The column itself is constructed as an active structure that means the correct geometry is guaranteed by commands of the intelligent

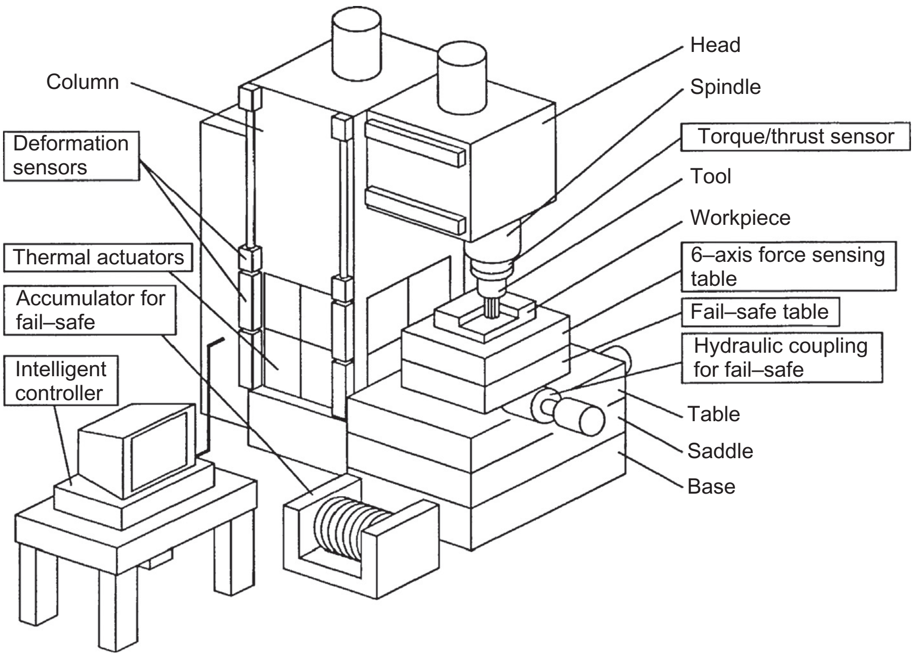

Figure 18.18 Hardware structure of the intelligent machining centre [22].

controllers. Vision and sound sensors are installed outside the machining centre to monitor the overall process performance (see also Fig. 18.11 for further development of machine intelligence).

Basically, in intelligent manufacturing (machining), the intelligent controller is used together with the standard CNC controller, as shown in Fig. 18.19A.

In particular, this intelligent machining system incorporates an intelligent machining module (IMM) which runs on existing commercial CNC systems, in this case on a digital signal processing board with multiple signal processing A/D and D/A channels. Various intelligent machining tasks, such as adaptive control (AC), TCM and process control, can be simultaneously performed in this system. The user can reconfigure the system by using script commands from the supplied signal processing and data collection library. The IMM is configured to communicate with commercial semiopen CNCs through the PC-CNC communication links and software. Some five-axis machining centres controlled by a FANUC CNC with a PC interface perform AC, chatter detection and tool-breakage detection [15]. More details on chatter detection can be found in Section 8.4. The IMM sends feed and spindle speed change, machining stop, tool change, tool offset and other commands accepted by the CNC controllers. Recently, sensor fusion is extensively developed in order to implement a multisensor reconfigurable monitoring system, shown in Fig. 18.19B.

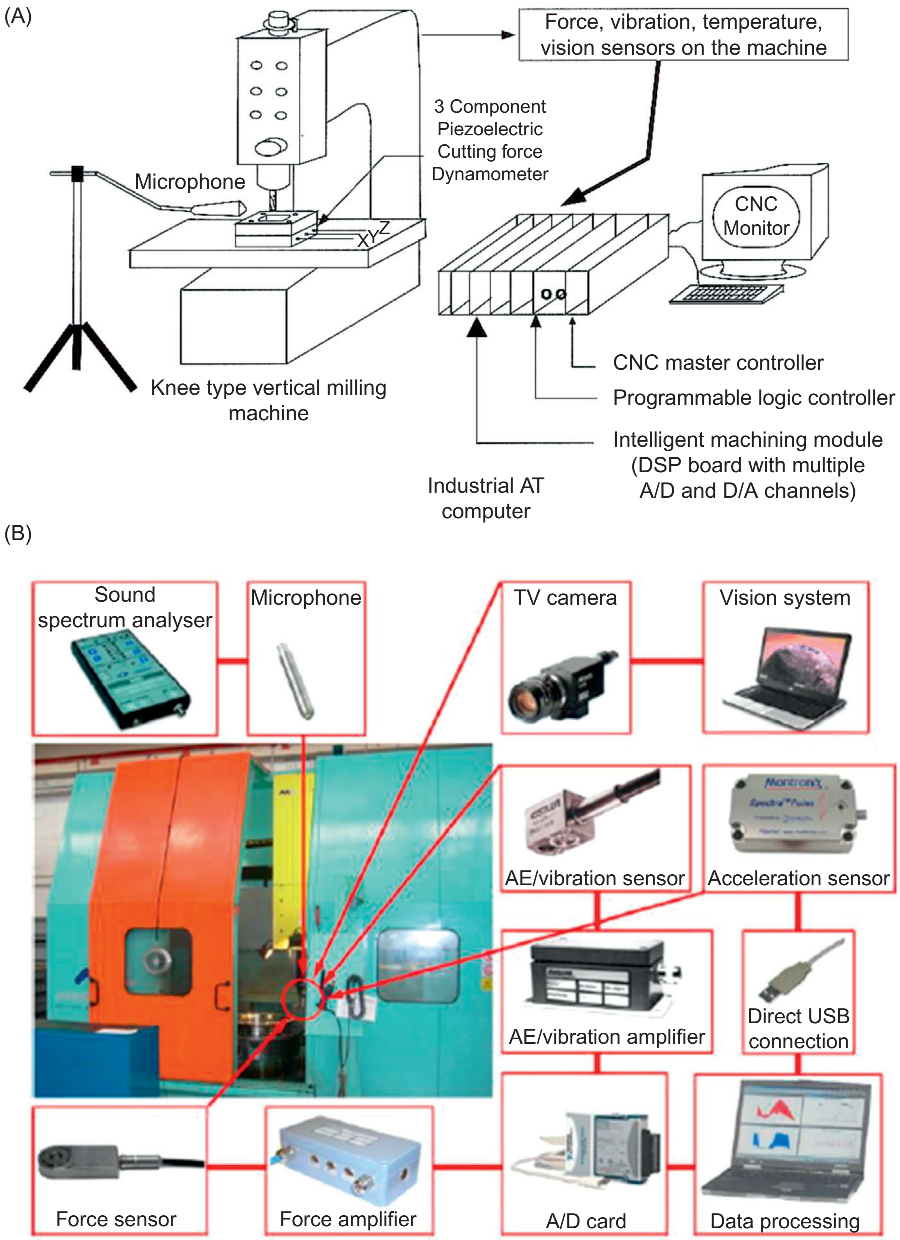

Figure 18.19 Sensor-assisted intelligent machining system [15] (A) and a concept of reconfigurable multisensor monitoring system [5] (B).

AC systems for metal cutting processes are a logical extension of CNC systems. The term AC denotes a control system that measures certain output process variables, such as spindle deflection or force, torque, cutting temperature, vibration amplitude and power. AC systems use a variety of sensors and control strategies and can be classified as adaptive control with constraints (ACC), adaptive control with optimization (ACO) and geometric adaptive control (GAC). It should be noted that the ACO system is the most general but it is difficult to implement; thus, the suboptimal ACC and ACG strategies are often used [23]. The ACC-type systems are well fitted for rough cutting, and the GAC-type systems are typically used in finishing operations, more successfully in grinding. An ACC system is basically a feedback loop where the feed adapts itself to the actual cutting force and varies according to changes in work conditions as cutting proceeds. In GACs, part quality is maintained in real-time by compensating for the machine tool temperature as well as for the deflection and wear of the cutting tool. The purpose of the compensation may be to improve the part dimension accuracy or the surface quality. In general, commercial AC systems used in production today for rough milling and turning are of the ACC type. Typically, ACC systems are based on the measurements of a single process variable, such as force, torque, or motor current, and try to maintain that variable at some predetermined value. A block diagram of an ACC system with the maximum cutting force as a constraint is shown in Fig. 18.20.

The AC algorithms determine new feed command to minimize the force errors between the reference and measured values. Most ACC systems attempt to maximize the metal removal rate by operating at a maximum feed rate compatible with maintaining a reference constant load on the milling cutter. An example of such a system, shown in Fig. 18.21, operates also on the principle of maintaining a constant radial force acting on the cutter during the milling operation. The cutting forces and spindle torque are continuously measured using four-component dynamometer shown in Fig. 6.7. The feed rate is reduced to compensate the force increase due to appropriate decreases in the process variables (e.g., due to increased workpiece hardness or depth

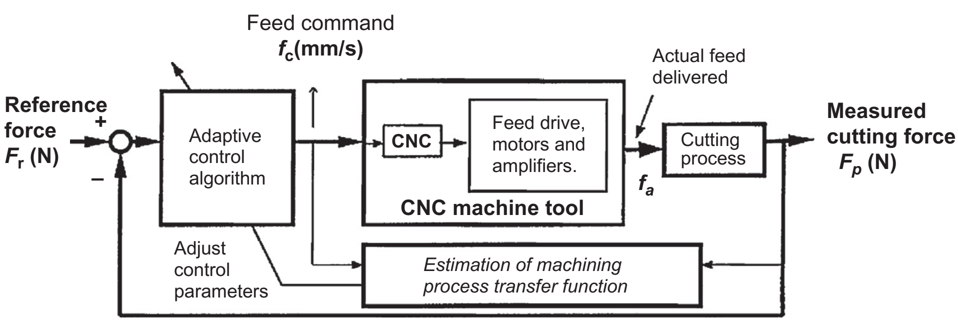

Figure 18.20 Block diagram of a general adaptive control system in machining [15].

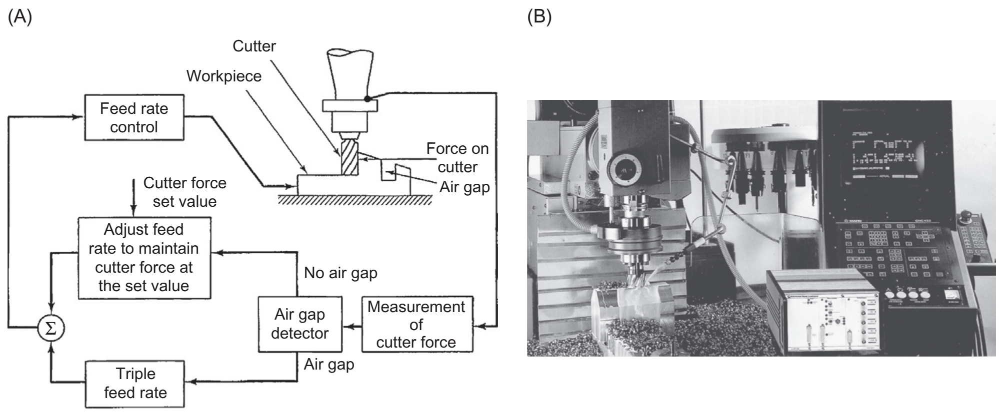

Figure 18.21 Configuration of typical ACC machining system [24] (A) and its implementation on CNC milling machine with piezoelectric force and torque sensors [25] (B).

of cut) or air gaps detected. In the latter case, when the actual cutter force is below a low threshold value, the CNC controller generates a new command to double or triple the feed rate.

New trends in AC systems involve variable-gain AC systems that can adapt controller gains to changing process parameters, ACO with on-line tool wear sensing using AE sensors and their complete integration into CNC systems, as well as into CAD/CAM/CIM systems in the future with broader applications of expert and process monitoring and diagnostics capabilities.

18.3 TOUCH-TRIGGER PROBING AND LASER MEASURING SYSTEMS

Generally, the measurement process can be divided into four sequential tasks: positioning, probing, measuring and evaluating [26]. The basic task of probing is when the target point is within the probing's measuring range and a physical linkage between the touching element and the surface is established. It should also be distinguished between hard probes, touch-trigger probes and measuring probing systems. In hard probing using dial indicators, the sensor for detecting the contact between measured workpiece and probe is the operator or a current measuring instrument. For a touch-trigger probing system, the final output is Boolean signal that indicates contact or no contact. A trigger signal is generated when a surface is touched by the moving tip ball or when the tip ball leaves the surface again. In contrast, measuring systems provide quantitative information about the position of the tip ball with respect to the reference point, which is needed for scanning. In general, four main modes of signal transmission are applied, namely: optical (infrared, IR), radio frequency, inductive and laser.

A huge variety of probing systems for performing different measurement tasks on the shop floor, as well as in the metrological environment, have been developed. In the case of coordinate measuring machines (CMMs) installed in special metrological labs, probing systems must ensure reproducibility of the sensing operation, even in the submicrometre range. Recently, two additional trends in the application of probing systems in the manufacturing environment, including on-machine inspection probing performing on CNC machine tools, and incorporating high-speed CNC CMMs into manufacturing plants in conjunction with CNC machine tools, are observed [25,27]. It is possible to couple directly CNC measuring machines (e.g., those from the MACH CMM series by Mitutoyo, which operate at feeds of 18,000 mm/second and 1.8 g acceleration [25]) with some CNC machine tools for concurrent inspection of machining operations. They can provide pre-/post-machining feedback to machine tools for machining adjustments. In addition, if an automatic part handler/feeder is integrated into the CMM machines, it operates between the CNC machine tool and CMM and completes the manufacturing system. Typical applications of on-machine probing systems include setup, measuring and inspection tasks for both workpiece and tool, usually by programmed probing routines during workpiece machining, as shown in Fig. 18.22.

According to the feedback from modern manufacturing plants, there are some standard applications of touch-trigger, on-machine probing measuring systems, which globally provide multiple benefits, as follows:

- Fast setups and automated machining of complex geometry parts.

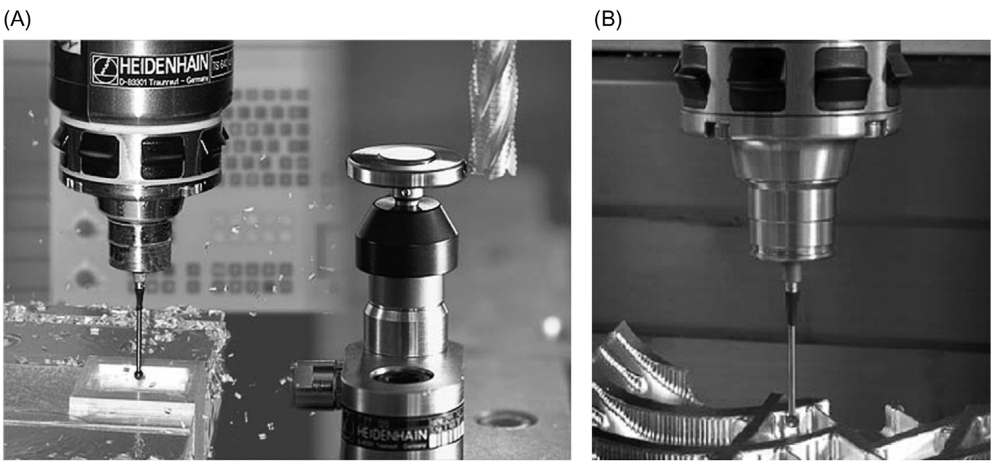

Figure 18.22 Examples of on-machine probing for tool and part measurements: (A) Measuring workpiece between machining cycles and tool presetting. (B) Part inspection [25].

- Identification of the type and size of parts, and their alignment in the fixture.
- Simplification of traditional fixtures by coupling a pallet fixturing system with machine/tool probes because the probe locates everything and compensates before machining.
- Tool presetting and detection of blunt or broken tool.
- Checking tools, verification of setups and adjusting offsets.
- Substantial reduction of scrap rate almost to zero.
- Detection of a pallet without clamping by providing error message to the control system.
- Routine machine calibration.

The 3D touch probes with wire and wireless signal transmission shown in Fig. 18.23A and B is specially suited for installation particularly on milling machines and machining centres. Probes from Fig. 18.23A and B is mounted in the machine spindle and can be used for CNC-controlled machine tools with manual (a) or automatic (b) tool changer. They can perform workpiece alignment, datum setting, workpiece measurement and digitizing 3D surfaces.

The probe from Fig. 18.23B features an integrated blasting unit: the probing point can be cleaned of loose particles with the aid of compressed-air or cooling liquids through three jets at the bottom of the probe. Chip accumulation in pockets allows automatic measuring cycles during unattended operation. The blasting unit can only work on machines with a compressed-air or cooling fluid duct through the spindle. Fig. 18.22A shows a 3D touch-trigger probe with a revolving touching element and an optical switch as a sensor used to measure length and diameter of the tool mounted in the spindle during rotation or while it is stationary. The tool touch probe is mounted in a T-slot on the table. The optical switch consists of an LED, a lens system mounted onto the stylus and a different photo-diode detecting the movement of the light spot caused by the movement of the lens system.

The NC control automatically saves the results of measurement in the tool tables. This probe can be used to measure tool wear during machining between any two

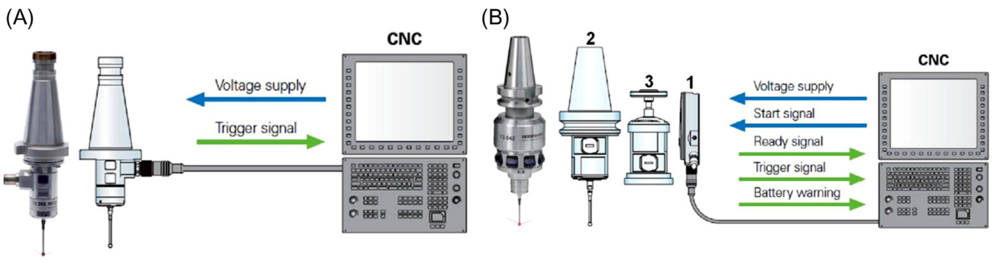

Figure 18.23 3D touch probes for machine tools [25]: (A) Probe with cable (hard-wired) signal transmission. (B) Probe with wireless signal transmission: 1- transmitter/receiver unit, 2-workpiece touch probe, 3-tool touch probe. *From Heidenhain.*

machining steps and automatically compensate it during subsequent machining operation, and also to check a tool due to tool-breakage monitoring. Probe accuracy of $\pm 15\ \mu m$ and probe repeatability from one direction of $2\sigma \pm 1\ \mu m$ at a probing velocity of 0.4 m/minutes are achievable.

As shown in Fig. 18.24, 3D touch probes can differently scan the surface model and transmit the data to create the CNC programme for the relevant part. Depending on the CNC control or the digitizing software available, the scanning process can generate a meander, unidirectional linear or contour line path.

A radio transmission system (Fig. 18.25A) provides communication between the probe and the machine's controller for a long distance, up to 15 m path length. The

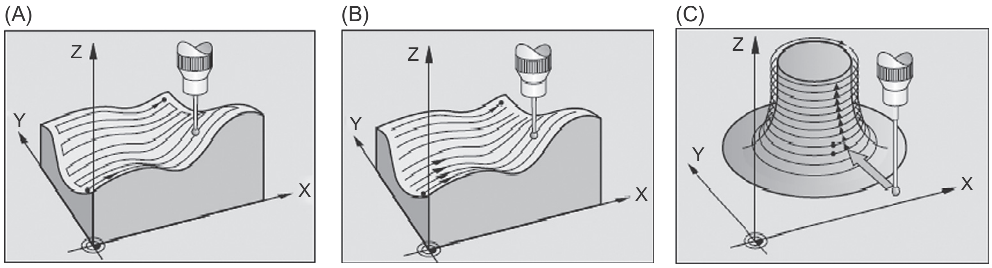

Figure 18.24 Types of digitizing: (A) Meander digitizing. (B) Line-by-line digitizing. (C) Digitizing along contour lines [25]. *From Heidenhain.*

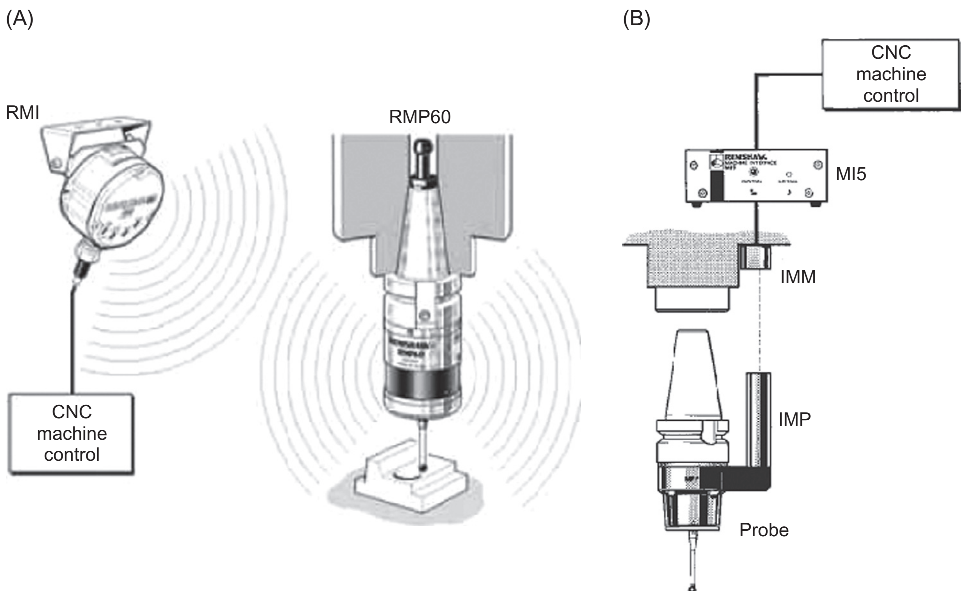

Figure 18.25 Radio transmission (A) and inductive transmission systems (B) [25]. *From Renishaw.*

radio transmission probe receives signals from machine control and transmits probe status signals to the CNC controller in 'operating mode' using the radio machine interface (RMI). The RMI converts it into a form compatible with the CNC programme. Operating modes include workpiece measurement and setup on medium to large horizontal, vertical and gantry machining centres, five-axis machines, twin-spindle machines and vertical turret lathes. An inductive transmission system (Fig. 18.25B) works by passing power and probe signals across a small air gap between two induction modules—inductive probe module and machine tool module (IMM). Probe signal is converted into a form accepted by the CNC controller by means of machine interface unit (M15). Inspection systems with inductive transmission of signals can be installed on machining centres and lathes (not recommended for retrofit installations).

Three-dimensional touch probes with infrared (optical) transmission signal (Fig. 18.26) transmit the trigger signal over an infrared light beam using a transmitter/receiver unit. This feature makes it ideal for use on machines with automatic tool changers. It can be mounted in both vertical and horizontal spindles, as well as in swivel spindle heads. The transmitter/receiver features two multicolour LED indicators that continuously display the condition of the infrared transmission and the touch probe (deflection and battery capacity). In the optical transmission system shown in Fig. 18.26A, signals are transmitted to the optical machine module (OMM), which is hard-wired to a machine interface (MI) unit (MI12). The functions of the OMM and MI unit can be integrated into a single module – the optical machine interface, as shown in Fig. 18.26B. Probes specially designed for high-speed machine tools can be used in this signal transmission system.

Tool setting probing systems for CNC lathes, termed high-precision pull-down arm (HPPA) and high-precision removable arm (HPRA), are shown in Figs 18.27

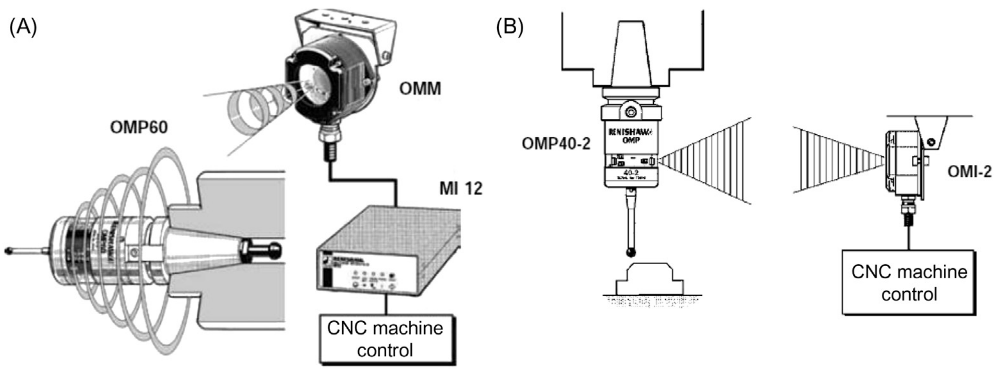

Figure 18.26 Trigger signal transmission for touch probes using optical transmission: (A) Horizontal machining centre. (B) Vertical machining centre [25]. *From Renishaw.*

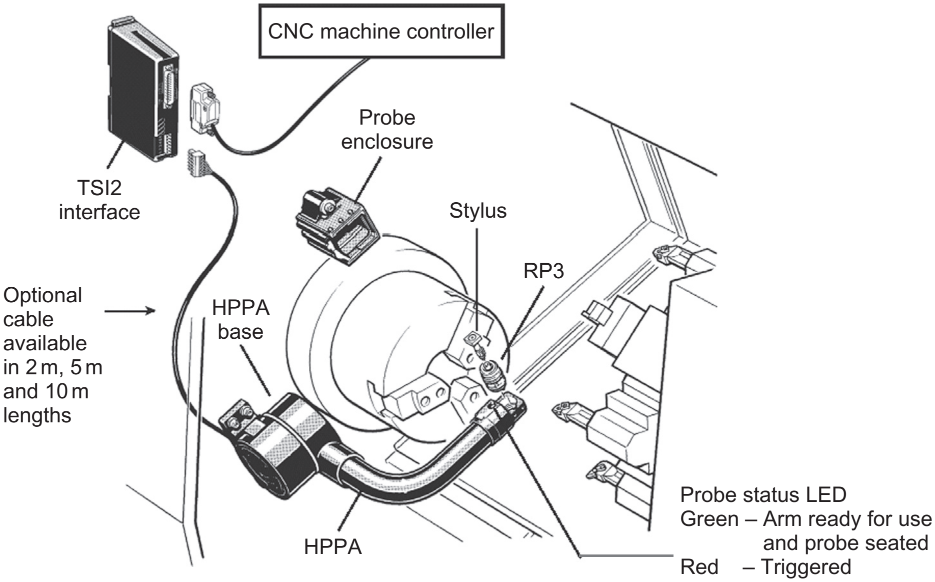

Figure 18.27 HPPA pull-down arm installed on a horizontal lathe [25]. *From Renishaw.*

and 18.28, respectively. The HPPA is a manually operated 'pull-down, push-up' system that is permanently located within the horizontal turning centre and used for tool setting operations. Automatic locking of the arm by special rotary device enables the probe's stylus to be relocated to within 5 μm (2σ). On the other hand, the HPRA is a 'plug-in' arm that is manually located inside the machine for tool setting, and removed once it is completed. The variation of arm location is about 5 μm (2σ). In addition, the high-precision motorized (electrically powered) arm (HPMA) and high-precision generic arm with special rotary kinematical design are available for in-process automatic tool setting and broken tool detection. The HPMA tool setting system is fitted to a horizontal machining centre with a multi-pallet changer.

The laser control, in-process tool management system shown in Fig. 18.29A monitors tools in real time within the machining environment, and certifies that the correct tool is intact within the specified tool-holder. It also verifies length, diameter, roundness, and run-out with a repeatability of lower than 1 μm. Moreover, this non-contact tool measurement system allows real tool length and flight circle deviation, as well as thermal drift of machine CNC axis and tool, to be determined and compensation automatically programmed into CNC control. Tool wear can be detected with an extremely accurate form control cycle, which compensates for a worn tool or change in a spare tool from the tool magazine. The system operates as part of the machining cycle and does not involve setup time or downtime, or require the spindle to stop for tool measurement. Delicate or small tools can be measured without

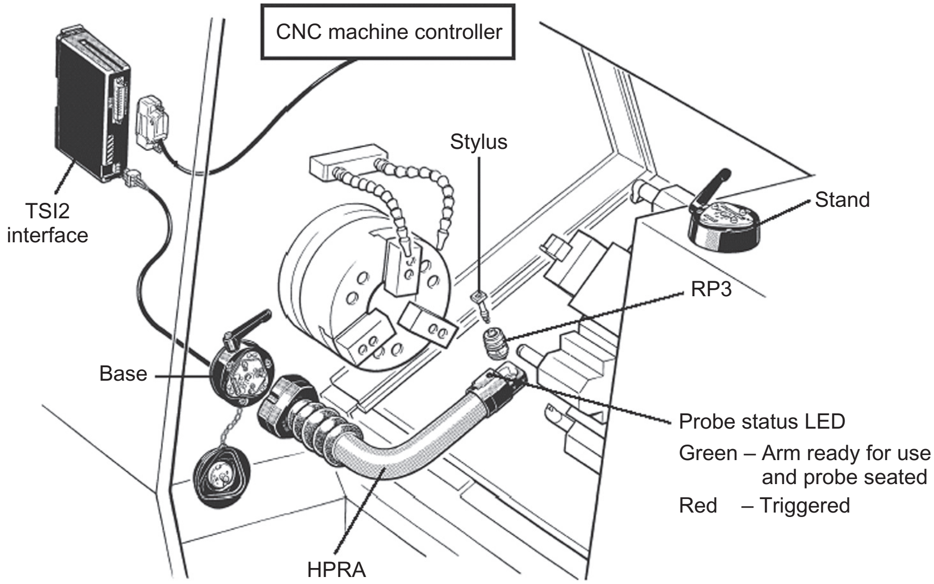

Figure 18.28 HPRA removable arm [25]. *From Renishaw.*

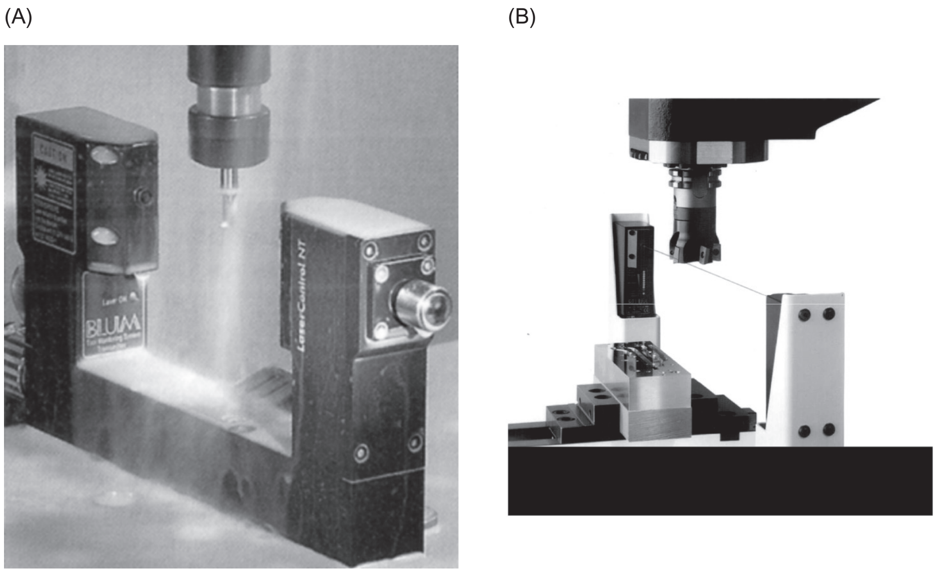

Figure 18.29 Laser system for monitoring of tool breakage (A) and optical presetting of cutting tool (B) [25,28]. *From Blum LMT and Renishaw.*

reducing their life through contact. For example, the TL Micro and TL Nano laser systems by Renishaw (Fig. 18.29B) permit the measurements of miniature cutting tools whose diameters are at least 0.03 mm with an accuracy repetition of down to ±0.2 μm. The laser systems can be installed in a CNC machining centre, and a precision of a few microns in measuring and tool setting is commonly achievable. They can be suited to the standard spindle speeds and high speed cutting spindles with over 30,000 rpm. It should be noticed that the deviations of the centreline (flight circle deviation) and length positions of tool arising at high spindle speeds can be determined and compensated automatically into the CNC control programme.

Measuring cycle routines include the length of concentric tools, such as twist drills, starting from 0.05 mm diameter, tap drills, engraving needles and reamers; eccentric tools, such as end mills, face mills, milling cutters of unknown length and diameter; and single cutting edge monitoring at the rounded edges of ball-nose cutters with cylindrical or conical shafts. Software measuring routines have been developed for Siemens, Fanuc, Heidenhain, Num, Fadal, Boston Digital, Okunta, Haas and other CNC controls. The laser system can be easily retrofitted to vertical and horizontal machining centres, including today's ultra-high-speed models.

Advances in software for programming probing routines are one of the main drivers simplifying probe use. In particular, new CAD/CAM software can produce a probing plug-in for process control and inspection at the same time as the machining tool paths are generated [27]. The plug-in supports probing routines to set tool length and diameter, perform workpiece identification and setup, in-process tool offset control and part inspection. The entire process can be fully simulated before machine prove-out. Consequently, on-machining probing becomes a natural part of technological process, and the probe is used as any other tool in the magazine.

Scanning probes provide faster data acquisition needed for form measurement, and due to this fact they are particularly suited to determining functional fits including cylinders, bores, valve seats, gears, etc., where variation and deviation are critical. As reported, conventional scanning systems generally take measurements at less than 20 mm/seconds but high-scanning systems allow the same task to be performed at a scanning speed of about 100 mm/seconds (i.e., faster by a factor of 10 or more [29]). An example of a probe suitable for very fast scanning is shown in Fig. 18.30A. When using a machine dynamics compensation algorithm (so-called Renscan DC), the probing cycle times on powertrain components shown in Fig. 18.30B and C can be reduced by a factor of four [20]. The SP25M probe uses the parallel kinematic system which is assembled out of one linear and two rotational axes resulting in a nearly hemispherical measuring range of 0.5 mm radius. In addition, it employs an $X-Y$ pivot mechanism featuring a compact membrane (planar) spring. By optical measurements via two mirrors on the scan module, all movements of the stylus can be measured without any inter-axis error and with resolution of about 0.1 μm. The probe

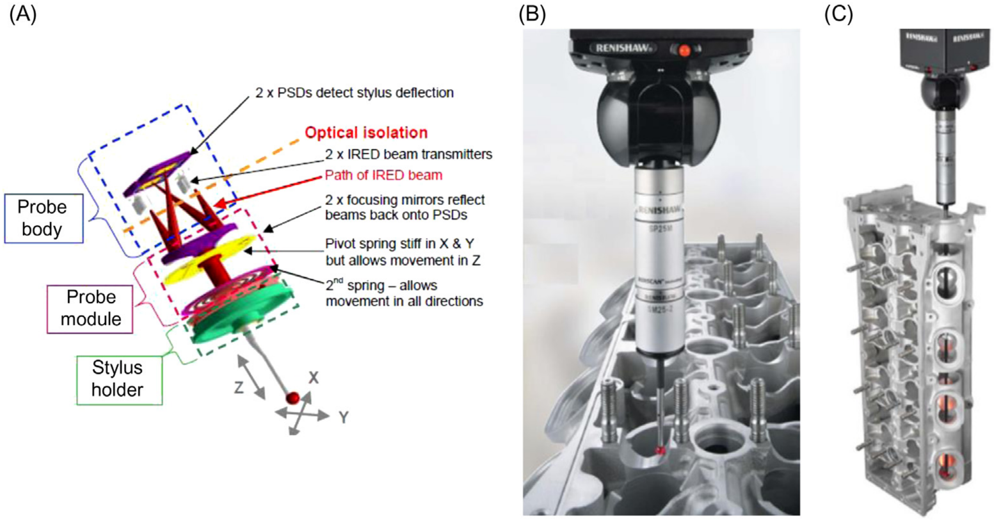

Figure 18.30 High-speed scanning probe; Renishaw's SP25M (A) and its use in measurements of cylinder (B) and cylinder head (C) bores [25,29]. *From Renishaw.*

uses three scanning modules optimized for different stylus lengths, and the longest stylus version is of 400 mm (Fig. 18.30C).

A non-contact measuring technology known as *machine vision* was implemented in manufacturing to replace human vision, because the requirements of many manufacturing processes have surpassed the limits of human eyesight. Manufactured items are often produced too quickly or with tolerances too small to be analyzed by the human eye. In a typical machine vision application, a video camera positioned on the production line captures an image of the part to be inspected and sends it to the machine vision computer. The computer then uses sophisticated image analysis software to extract information from images and generate decisions about those images, such as [25]: locating objects accurately even within complex or confusing scenes, inspecting objects to ensure quality and consistency, identifying objects by analyzing their shapes or by reading serial numbers on their surfaces, and automatically making measurements. Once the vision system has processed the image and made every necessary analysis, the inspection result is then communicated to other equipment on the factory floor, such as an industrial controller, a robotic arm, a deflector that removes the part from the assembly line or a positioning table that moves the part. Machine vision sensors offer manufacturers highly accurate and cost-effective methods to help improve quality on the factory floor with the latest vision sensors for in-process inspection systems. Advances in machine-vision gauging systems include more powerful sensors and laser-based gauging systems. With the latest techniques, manufacturers can improve shop-floor measurement with systems featuring lower cost, greater durability, increased precision and ease-of-use that can make machine-vision sensors for gauging a more viable alternative to contact gauging. High precision applications such as the automotive and aerospace industries demand in-process gauging systems capable of delivering the products when manufacturers employ vision systems on the factory floor. Laser-based inspection/measurement systems shown in Fig. 18.31 use CCD technology similar to those of vision systems, but employ a laser light source with very high precision for gauging applications instead.

Costs of vision sensors for gauging are compared to PC-based vision systems. In some industrial factory applications, resolution requirements for sensor gauging are also not as high as those provided by higher-end PC-based vision systems that measure submicron-sized components for industries, including semiconductors or nanotechnology.

The Z500 laser-based sensors shown in Fig. 18.31 enable higher precision measurements because for laser-based sensors their own laser light source behaves like a highly controlled light element, a pinpoint beam with approximately a 10 μm spot diameter. Using vision sensors, users primarily perform pattern matching for surface defects, but the laser light source sensor creates almost a cross between a sensor and the 2D vision CCD element with high precision. When inspecting the parts, the system can perform gauging or measuring with the ability to measure the height of the object, by moving the object or the sensor, within several microns. The CCD element monitors the profile of the reflected light, so light comes down like a fan-type, wide beam, and then it can measure diversely shaped objects (also with round shapes) in a stable manner. In a line beam method, a 2D sensor head (SW-CCD) receives the reflected light to measure accurately the 2D profile of the measured object. A 2D sensor head (SW-CCD) receives the reflected light to measure accurately the 2D profile of the measured object.

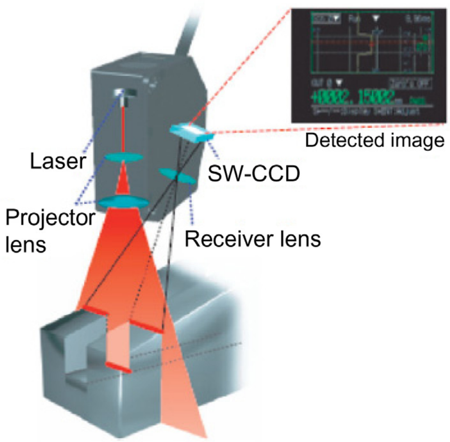

Figure 18.31 In-line inspection using vision sensors based on line beam method [25].

18.4 SENSOR-GUIDED AND INTELLIGENT/SMART TOOLS

Recently, cutting tools that can monitor the machining process and communicate the actual status are of a great interest to automated manufacturing. In general, many types of sensors described previously can be installed into tooling, depending on the accuracy and difficulty of the monitoring process. Using sensor(s), transmitter and appropriate electronics with subprograms residing in the machine control systems, creates intelligent, high precision and highly productive cutting tools. A scheme of the closed-loop electronics for such an IT is shown in Fig. 18.32.

The built-in servomotor, shown in Fig. 18.33, actuates the motion of the tool by harmonic drive, proving a fourfold oversampling at 800 kHz for fast and trouble-free operation. Moreover, this tool is designed with additional machine axis control (e.g. U-axis) which can perform more complex contours. New features of ITs include communication with the machine control system and the possibility for self-adjusting in automatic mode to variations resulting from critical events during machining processes.

The sensor-guided boring bar, termed *smart or intelligent tool*, with the ability to correct the cutting-insert location, is shown in Fig. 18.34A. This design was the result of implementing 'agile line boring' (called BOA, for boring with optimal accuracy [32]) for cam and crank bores which are especially difficult to machine due to very high length, and both dimensional and geometric precision. Protection against error-causing vibrations and elimination of tool deflections were two construction challenges. In addition, even a 3—6 m distance between an off-board controller and a tool in conventional machine causes unacceptable signal delays. So, active machining control requires a new tool sensor and controller to continuously sense and provide

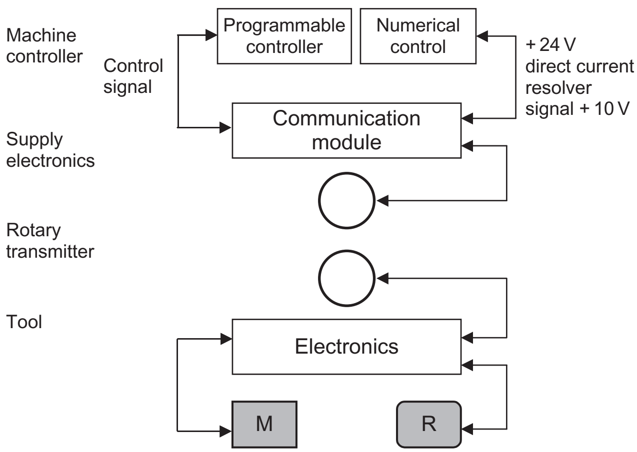

Figure 18.32 Closed-loop control electronics used for intelligent tooling [31].

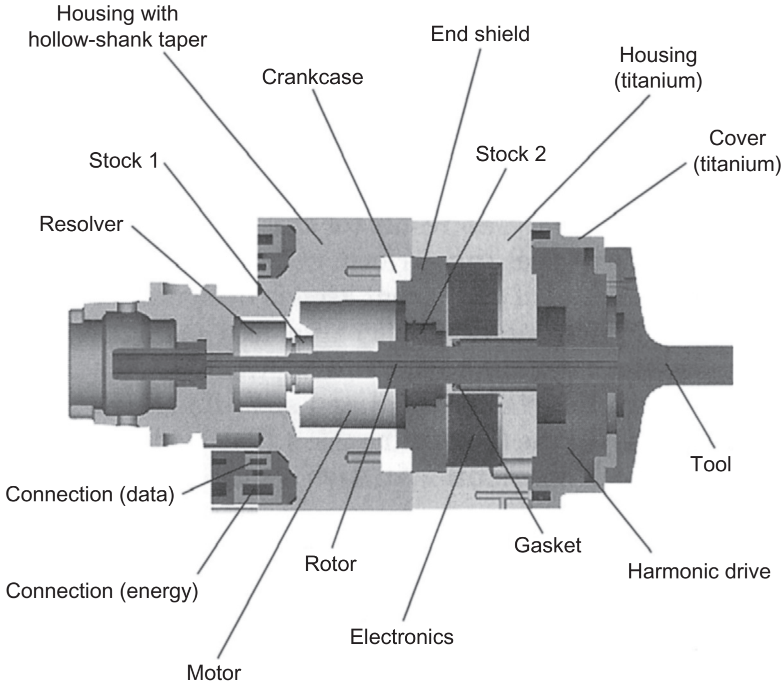

Figure 18.33 Electronically activated feed-out system for actuating tool motion [31].

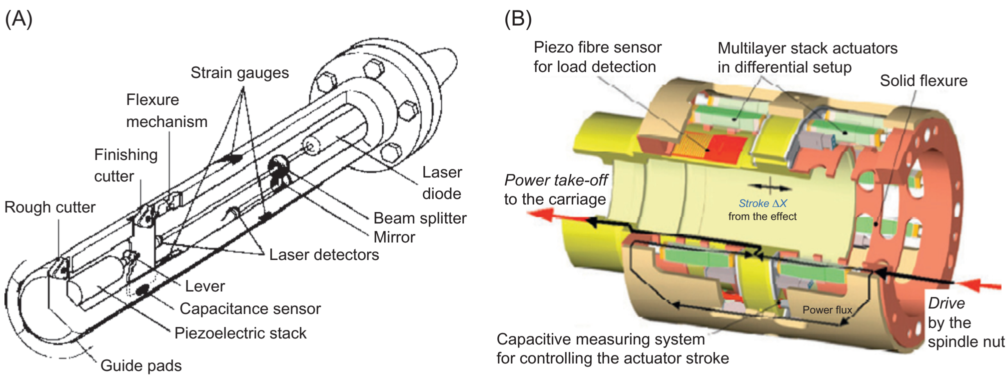

Figure 18.34 Sensor-guided boring bar [32] (A) and axial vibration compensation unit [33] (B).

feedback. The tool shown in Fig. 18.34A, rotating at 5,000 rpm, has a built-in computer, a laser guidance system and piezoelectric sensors housed within the tool body. For this reasons, the boring bar has a hollow construction to contain actuators and sensors for real-time control. The tool is equipped with two cutting inserts, for roughing and finishing the bore respectively. The finishing cutting insert, mounted on a flexure member inside the hollow tool, connects to a piezoelectric actuator with a very high-frequency response. Tool controller outputs feed into the piezoelectric actuator, which turns them into linear impulses, and transfers to the flexure member through a lever. The lever moves the finishing insert radially just enough to cancel out the effect of vibration in the boring bar, workpiece, or machine tool. Strain gauges on the tool OD provide more loading and displacement data. Inside is an ultra-precision laser system that measures vibratory displacement and an actuator that corrects the cutting-insert location. In addition, Fig. 18.34B presents the design of an axial vibration compensation unit which uses piezo-fibre sensors as vibration sensors. This allows compensation for vibrations in the drive train for which the bandwidth of the feed drives in inadequate [33].

Fig. 18.35 shows a micro-adjustable boring head with a direct absolute measuring system fitted to the adjustment slide, a servomotor and an infrared electronic transmission and receiving system (Fig. 18.35B). The micro-adjustable system termed KomTronic-Electronic Compensating System by Komet [25] is incorporated into the closed loop. The external inductive power supply is provided, and the system can perform fully automatic adjustments of micrometre range in the diameter without manual intervention. A resolution of 1 μm in the diameter along with high repeatability and reliability is achievable when used on machining centres, flexible manufacturing lines, and special transfer lines.

Fig. 18.36 shows a new generation of micro-adjustment boring systems featuring dynamic balancing and the U axis drive. Apart from dynamic balancing, the drive

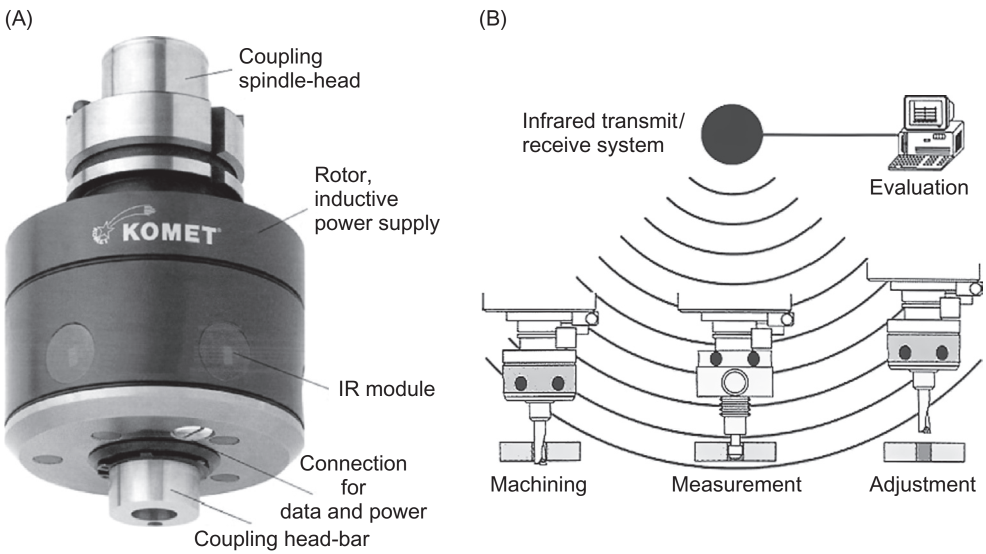

Figure 18.35 Micro-adjustable boring head with IR module (KOMET-M042) (A) and closed-loop micro-adjustable system [25] (B). *From Komet.*

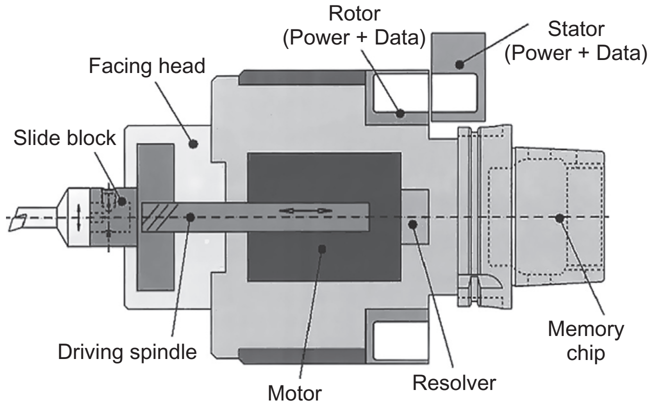

Figure 18.36 Actuated micro-boring system — KomTronic *U* axis system with dynamic balancing feature [25]. *From Komet.*

torque is minimized due to diverting the centrifugal forces onto reactive forces exerting on the housing and building up the balancing element and the slide tool system into the drive line. The KomTronic *U* axis modular system mainly consists of a compact single slide that is driven by means of a servomotor and treaded spindle. A measuring system is incorporated into the feed unit. Data and power transmission are noncontact. This allows the cutting edge length to be adjusted radially to the axis of rotation (*Z*). Hence, if connected to the NC machine control system, the *U* axis can be interpolated with the *Z* axis. Programming is performed using standard NC programming language. The boring system can be classified as an intelligent tooling system because it can be used for multiple machining operations on machining centres with intelligent placement of the cutting edges.

Fig. 18.37 shows the mechatronic tool system (termed TOOLTRONIC by Mapal [34]) for stationary and non-stationary applications on machining centres (Fig. 18.37A), including machining contours, recesses and noncylindrical bores. Using inductive and bi-directional data transmission, the tool system provides a full NC-axis that is incorporated into the CNC control system of the machine tool. As a result, such functions as interpolation of various axes and adjustment for tool wear compensation and cutting insert radius can be utilized. The drive unit can be supplied with different MIs and different actuating tools can be flanged to the drive unit to perform specific machining tasks. Fig. 18.37B and C present both eccentric and linear actuating tools for high spindle speeds of 6,000 rpm and 4,000 rpm, respectively. In the first case, static unbalance is compensated by eccentric displacement and in the second case by weight compensation slide. The eccentric actuating tool is appropriate for small strokes, whereas the linear one for larger strokes. The application range can also include honing operations.

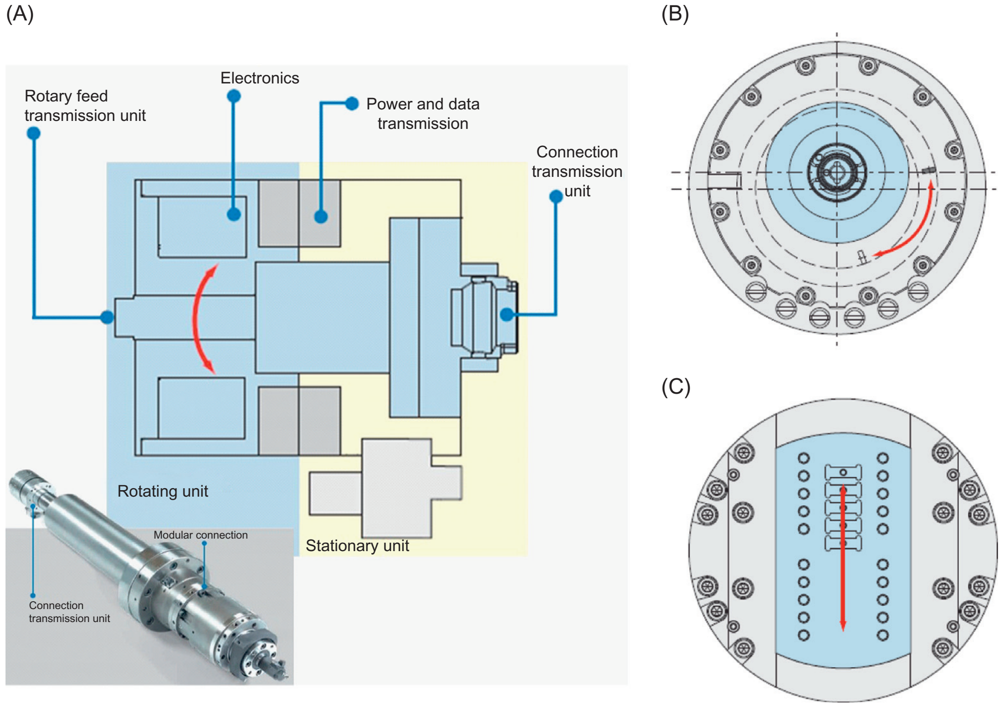

Figure 18.37 Actuated micro-boring system (A); eccentric (B) and linear (C) actuating tools [33].

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