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Real-Time Monitoring of High-Speed Spindle Operations using Infrared Data Transmission

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Abstract

High-performance cutting is carried out with high cutting and feed speeds. Particularly, the use of heavy cutting tools (e.g. in planing machines), it is important to monitor the clamping and balance condition of the mounted tool, as well as the process forces. Therefore, a real-time monitoring system for high-speed operations based on the IrDA protocol was developed. It could be shown that infrared data transmission systems allow shorter reaction times compared to conventional wireless LAN applications. The presented monitoring system provides a reaction time of 7.14 ms at a bandwidth of 42.5 kHz and a data rate of 4.1 MBit/s.

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Keywords: IrDA; real-time monitoring; process monitoring

1. Introduction

In high performance cutting (HPC) the cutting speed and feed speed is significantly higher than in conventional cutting processes. This makes it more difficult to attain a sufficient correlation between the required process parameter and the sensor signal. Process monitoring is generally carried out using sensor-integrated machine tool components or by monitoring the spindle/motor current. However, the bandwidth of the sensor system decreases with an increase in distance between the sensor and cutting zone (Fig. 1). This is particularly true when processing workpieces with a high mass; the eigenfrequency of the workpiece decreases and therefore the measurement error increases. For this reason, it is beneficial to locate the sensor directly within the rotating tool holder or the spindle shaft. [8]

The embedding of sensors and their electronic equipment into high-performance machining spindles requires a fast and reliable data transmission system in order to fulfil the sampling theorem. When data transmission is linked to a real-time monitoring system (e.g. safety devices), it is especially necessary to provide high data transmission rates with a low reaction time. Frequency hopping methods, which will be mandatory for wireless LAN applications in Europe from 2015, do not meet those requirements [1] [2] [4].

The aim of this project was to provide a minimum reaction time for high-performance wood machining processes with a feed speed up to 600 m/min. Planing machines are equipped with heavy cutting tools (up to 35 kg) that are clamped within belt-driven spindles using hollow shank taper systems. In contrast to conventional planing machines (double-sided bearings), this allows an increase in the rotational speed up to 12,000 rpm (cutting speed up to 100 m/s) and reduction in tool changing time. As imbalance mass quadratically increases with the rotational speed, a sensor-integrated machining spindle using thin-film sensor systems was developed [3]. This spindle allows monitoring of the clamping force, the balance condition of a mounted tool, and the cutting force. In order to increase the bandwidth (excitation frequency: 4 kHz) and allow to activate counter measures (e.g. due to critical balance conditions) with a minimum reaction time, a real-time monitoring system for high-speed spindle operations, based on

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an infrared data transmission unit (IrDA standard), was developed. The interface to the sensors is an analog-digital-converter (ADC), which allows the use of any kind of sensor (e.g. strain gauge, piezoelectric sensor) with the system.

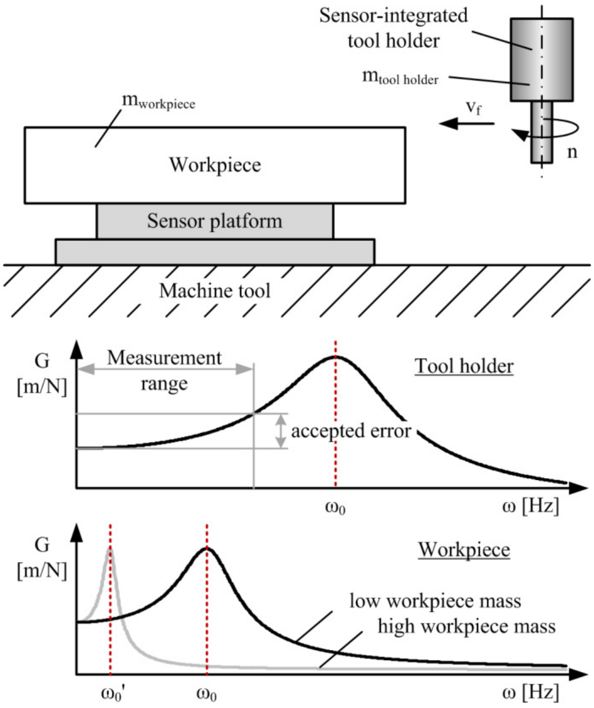

Fig. 1: Comparison of process force measurements using sensor platforms and sensor-integrated solutions

2. Infrared Data Transmission Unit

Machine spindle shafts are designed in order to achieve maximum stiffness with a minimum mass moment of inertia. Therefore, the major requirement of embedded data transmission units is a high data transmission rate with a minimum device volume on the rotating side. In Fig. 2 a comparison of common data transmission protocols is shown. Based on [6] and [7] the data transmission rate is plotted against the hardware and software complexity. The field of application of the standard ETSI EN 30028 (mandatory frequency hopping) is also indicated [6]. As illustrated, infrared protocols provide a higher data rate to complexity ratio. Therefore, infrared protocols, particularly for short distance applications (e.g. within machining spindles), are preferable to wireless LAN applications. Furthermore, optical communication systems are less sensitive to disruptions e.g. generated by motors or induction coils [12]. Current developments include ready-to-use IrDA protocol controllers and controller cores, which provide data rates up to 1 Gbit/s and programmable deterministic characteristics [9] [11].

The infrared data transmission unit is based on two systems: the embedded electronics within a rotating spindle shaft and a stationary evaluation unit (Fig. 3). On the rotating part, the amplified sensor signals are converted using a four channel 16 bit ADC. In order to guarantee zero data sampling latency, a simultaneous sampling ADC (type: MAX11047)

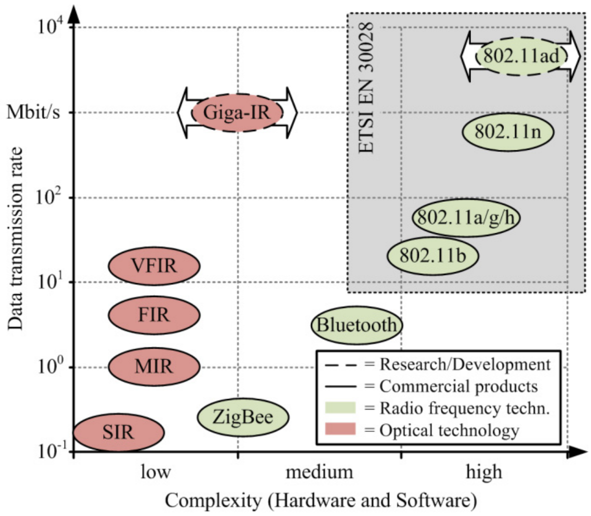

Fig. 2: Comparison of common data transmission protocols for contact-less data transmission (based on [6] and [7])

with a maximum sampling rate of 250 kSample/s was used. The ADC is connected to an Atmel 32 bit microcontroller (μC) with a clock rate of 66 MHz. The package type housing the microcontroller is TQFP-64 with a maximum number of 45 GPIOs (General-Purpose Input/Output), used for the parallel bus systems of the ADC and the IrDA protocol controller. The IrDA protocol controller (type: IPMS_IRHSP, Fraunhofer IPMS, [9]) is a separate integrated circuit with the package type SSOP28. The IPMS_IRHSP supports IrPHY VFIR (Very Fast Infrared) with a maximum data transmission rate of 16 MBit/s and allows exclusion of level 2 (IrLAP) and level 3 (IrLMP) of the OSI (Open Systems Interconnection) model, in order to use it as a data streaming system. The actual data link is carried out using two TFDU8108 transceiver modules, both of which are directly connected to the IPMS_IRHSP. On the stationary side, a larger, and therefore more powerful, microcontroller can be used e.g. to run process monitoring calculations or for data transmission using USB protocols.

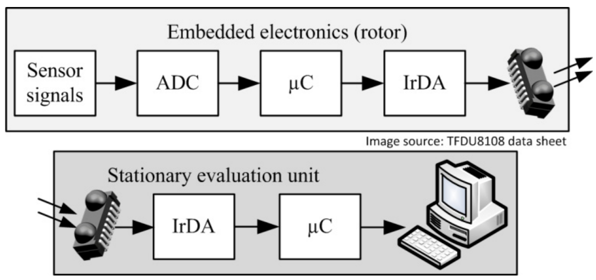

Fig. 3: Setup of the infrared data transmission unit

The infrared data transmission unit was set up and tested using two self-contained evaluation boards. In order to analyze different components of the data transmission unit, each component was soldered onto its own board; all main components (ADC, μC etc.) were selected with a minimum application volume. The rotor microcontroller evaluation board was linked to the ADC, the IrDA protocol controller and the transceiver modules using a base board (Fig. 4). The stationary evaluation unit was set up in the same way (excluding ADC) and linked to a personal computer using USB HiSpeed (Fig. 5). Data transmission between both evaluation boards is carried out by facing the transceiver module of each evaluation unit toward each other. In order to investigate the field of application, a simulated sensor signal with an excitation frequency of 4 kHz was generated and applied to the ADC on the rotating part.

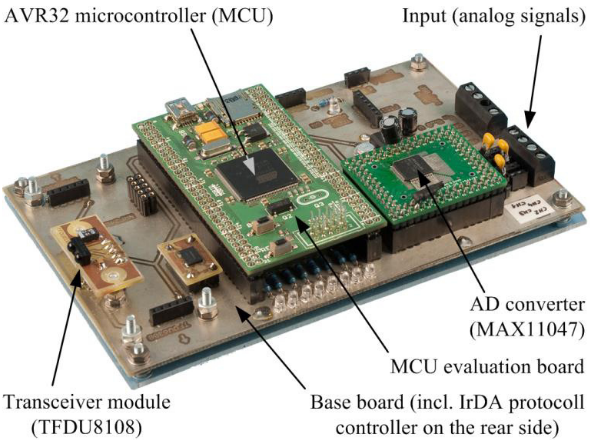

Fig. 4: Evaluation board of the rotating part

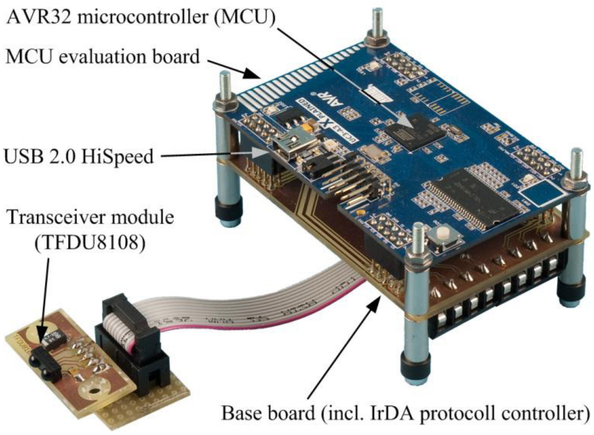

Fig. 5: Evaluation board of the stationary unit

In Fig. 6 the initial sensor signal (generated by a frequency generator) and the start of ADC conversion is shown. A maximum sensor sampling rate of 50 kHz can be achieved with the system. Fig. 7 shows the recorded sensor signal on the stationary unit. With this set-up, four 16-bit sensor signals were recorded at a time, with a bandwidth of 4 kHz and an oversampling factor of M = 6.25 (12.5 values per sine period). The maximum error between the initial and the recorded sensor signal was no more than 2.17 %.

3. Real-time monitoring system for cutting processes

The schematic design of a real-time monitoring system for cutting processes is shown in Fig. 8. The sensor unit converts and amplifies the desired process parameter into an analog signal, while the data transmission can be carried out using analog or digital data. When transmitting digital data, an ADC and a microcontroller with an internal or external protocol controller is used within the data transmission unit (cf. section 2). The monitoring unit is the main part of the real-time system. Within the monitoring unit, the sensor signals are conditioned (e.g. using filters) and pattern recognition is carried out. Appropriate algorithms allow an activation of process based and control based measures (e.g. rejection marking, emergency stop, actuating elements). A separate visualization unit is used for visualization purposes while the actual measurement signal can be recorded via the monitoring unit and the visualization unit. Thus, a computer based or stand alone data logger can be used.

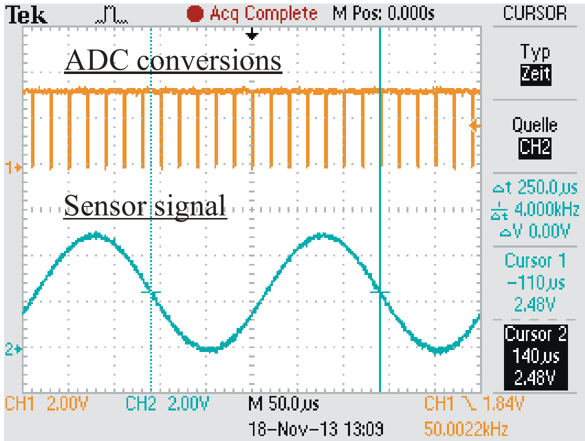

Fig. 6: Initial sensor signal (frequency generated) and ADC conversion

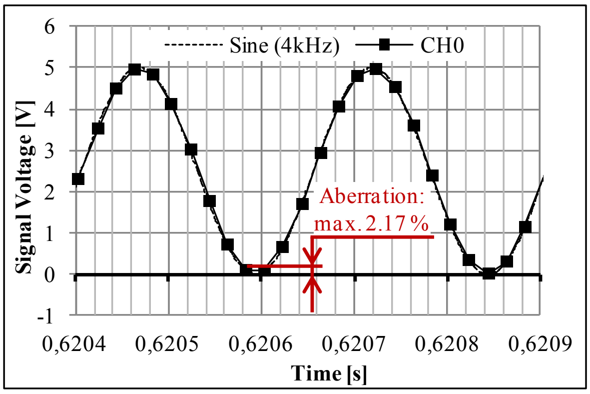

Fig. 7: Comparison of an ideal sine formed signal (4 kHz) and the recorded signal on the stationary unit

In order to fulfill real-time criteria within the monitoring system, the requirement for each unit (excluding the visualization unit) is a deterministic operation. Therefore, it is beneficial to disable the check sum strategies of the data transmission protocol (low bit error rate required). This reduces the reaction time and guarantees that required for the real-time system. Furthermore, no operating system should be implemented within the embedded hardware of all units. The advantage of firmware over operating systems is direct access to the hardware. Operating systems use an interrupting

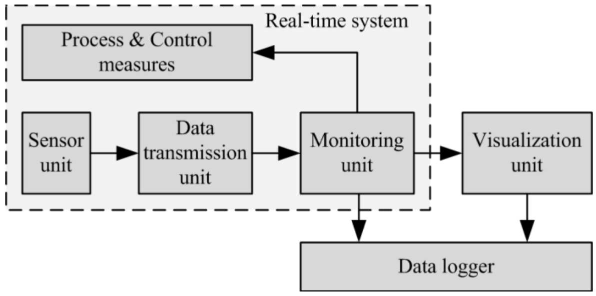

Fig. 8: Schematic design of a real-time monitoring system for cutting processes

hardware management system, which would not allow a guaranteed reaction time of the real-time system.

3.1. Monitoring unit

The reaction time between the detection of a critical value and the activation of a specific measure depends on the complexity of the calculation within the monitoring unit, the sampling rate of the ADC and the data transmission rate. Furthermore, high net data transmission rates require a high payload to frame size ratio. Therefore, the infrared data transmission was carried out with a frame size of 1544 Byte. Each frame consists of an 8 Byte header and 128 data packets with a size of 12 Byte. The data packets consist of four sensor signals, the actual rotation angle and a time stamp. On this basis, the infrared data transmission rate can be calculated to 4.83 Mbit/s, equating to a frame transmission period of 2.56 ms. Within this time, receival of the frame, conditioning of the signals and pattern recognition must be carried out within the monitoring unit. The tested calculation routine for signal conditioning and pattern recognition was based on the determination of the clamping and balance condition, as well as the process force, of a planing tool mounted within a wood machining spindle [3]. The required quantity and complexity of the calculation for each frame is shown in Table 1.

Table 1: Calculation routine

Description	Quantity	Complexity
Signal Calibration	512	32 bit = 16 bit x 32 bit + 32 bit
Compensation (temperature, rotational speed)	1024	32 bit = 32 bit x 32 bit + 32 bit
Low Pass Filter	512	$32\ bit = \sum_{i=0}^{100} 32\text{ bit} * 32\text{ bit}$
Calculations (clamping force, bending moment, process forces)	1536	32 bit = 32 bit x 32 bit
	2688	32 bit = 32 bit + 32 bit
	896	32 bit = 32 bit / 32 bit
	128	32 bit = sin(32 bit) x 32 bit
	128	32 bit = cos(32 bit) x 32 bit
	128	32 bit = atan(32 bit) + 32 bit
	128	32 bit = asin(32 bit / 32 bit)
	128	32 bit = sqrt(32 bit x 32 bit x 32 bit)

The calculation time of the initial Atmel microcontroller (AVR32) is 11 ms, which significantly decreases the potential data transmission rate. In order to reduce the calculation time and therefore the reaction time of the real-time monitoring system, the AVR32 microcontroller (MCU) was compared with a STM32 microcontroller and a ARM11 (Raspberry PI) microprocessor (MPU). The tested processing units differ primarily in respect to the clock rate and the internal architecture (Table 2).

Table 2: Characteristics of the tested processing units

Description	Clock Rate	Type	CPU	FPU	DSP
AVR32	66 MHz	MCU (32-bit)	AVR32	yes	no
STM32	168 MHz	MCU (32-bit)	Cortex M4	yes	yes
Raspberry Pi	700 MHz	MPU (32-bit)	ARM11	yes	no

CPU = Central Processing Unit FPU = Floating Point Unit
DSP = Digital Signal Processing Unit

In Fig. 9, the calculation time is plotted against the clock rate of the processing units. The interpolation between the measurement data of the AVR32 microcontroller and the Raspberry Pi microprocessor demonstrates the similarity of the internal architecture. The STM32 microcontroller is equipped with a DSP (digital signal processing) unit, which allows calculating common routines (e.g. linear calibration, low pass filter, multiplication) with a few clock cycles only. Therefore, the STM32 architecture provides lower calculation time in respect to the clock rate. For example, the Raspberry Pi with a clock rate of 700 MHz is only twice as fast as the STM32 with a clock rate of 168 MHz. Coupled with the more complex programming routine of the Raspberry Pi (in bare metal), the STM32 microcontroller was used for the monitoring unit. The STM32 reduced the calculation time to 1.82 ms with a corresponding sampling rate of 42.5 kHz.

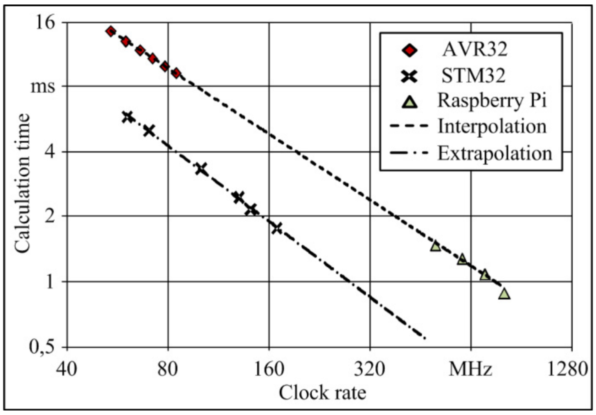

Fig. 9: Comparison of calculation time of two microcontrollers (AVR32, STM32) and one microprocessor (Raspberry Pi)

3.2. Experimental setup of the real-time monitoring system

The setup of the real-time monitoring system is shown in Fig. 10. It consists of the basic components of the infrared data transmission unit but the microcontroller on the stationary side is replaced by the more powerful STM32 microcontroller (ARM Cortex M4 processor). This allows the carrying out of all required calculations within the microcontroller on the stationary unit (cf. Fig. 8). The microcontroller is further connected to a personal computer; however, by using the personal computer for visualization purposes only, it is possible to meet the real-time criteria. Process and control measures can directly be activated through the microcontroller GPIOs.

In order to investigate a continuous, contact-less data transmission from a rotating shaft to a stationary unit, the monitoring system was built into a test stand. The test stand primarily consisted of a rotating shaft and a slip ring (Fig. 10). The rotational speed of the shaft can be adjusted up to 3,000 rpm. Three transceiver modules were mounted on the shaft using a base body with the dimension of a commonly used belt-driven spindle shaft (type: HSK F-80). The transceiver modules were connected to the IPMS_IRHSP protocol controller using a slip ring. On the stationary unit, a transceiver module was located within a housing built of aluminium sheets and with a cross section of a commonly used motor driven machining spindle. The stationary evaluation board, with its USB connection for visualisation purposes, was located at the end of the real-time monitoring chain.

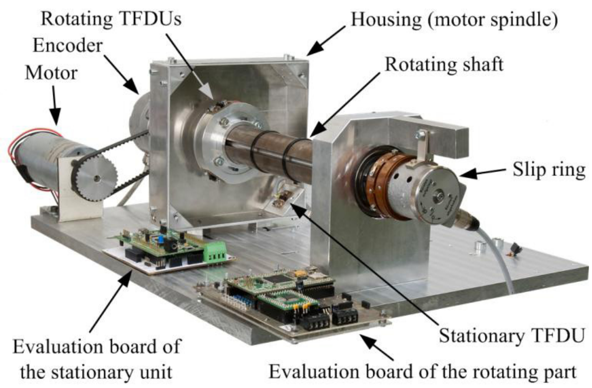

Fig. 10: Test stand for the evaluation of the real-time monitoring system

3.3. Determination of the maximum data transmission rate and reaction time

The reaction time in high speed monitoring systems is the time from ADC sampling until GPIO activation. In order to determine the reaction time of the infrared real-time monitoring system, the transmission sequences and their durations were measured using an oscilloscope (Fig. 11). In the beginning, the analog sensor values are continuously converted into digital characters. Once 128 packets have been sampled, the whole frame is sent to the IPMS controller. A TFDU transceiver module transmits data on the rotating part, while a TFDU transceiver module within the stationary unit receives and forwards the frame to the IrDA controller. Once the frame has been sent to the stationary microcontroller, each sensor value within each packet is calibrated, compensated and filtered before the actual calculations are carried out. In this manner, the monitoring system can immediately react to a critical sensor value.

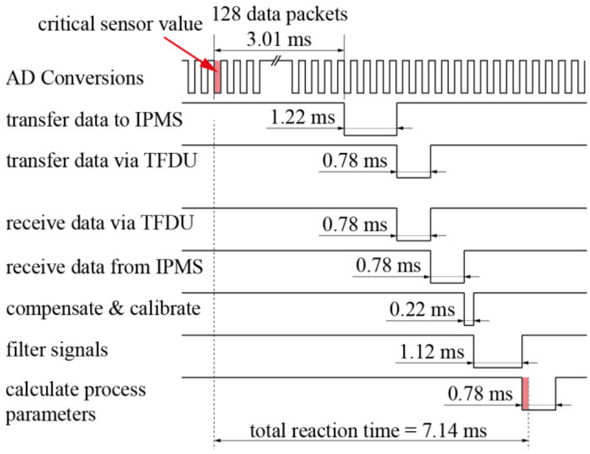

Fig. 11: Sequences and their duration of the real-time monitoring system

The reaction time of the monitoring system is longest when the critical sensor value is sampled within the first of 128 packets. Due to this, the test procedure was configured to manipulate the value of the first packet via pressing a user button on the rotating part. On the stationary unit, a GPIO was activated once the manipulated value was detected. A maximum reaction time of 7.14 ms could then be determined by parallel monitoring of the user button and the GPIO (Fig. 12). The minimum reaction time (critical value within the 128th packet) is 4.92 ms. In comparison to wireless LAN protocols (e.g. 802.11 b), the transmission time for a frame of 1500 Byte is approximately 5 ms [10]. Assuming the same time for AD conversion and the calculations that follow (compensation, calibration, filtering, process parameters), its reaction time would be 9.58 ms.

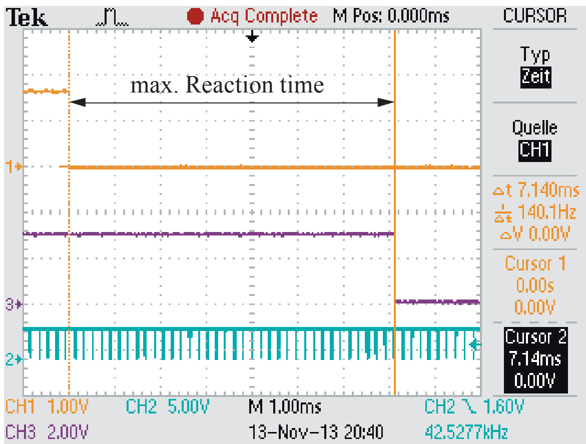

Fig. 12: Determination of the maximum reaction time and the sampling rate of the real-time system

The data transmission rate was determined by monitoring the CONVST pin (start of ADC conversion) on the rotating part (Fig. 12, optical interference). In this manner, the final maximum data transmission rate was calculated from the frame size (1544 Byte) and the frame transmission rate (42.5 kHz / 128 data packets) to be 4.1 Mbit/s.

4. Design concept for infrared data transmission

One advantage of wireless LAN applications compared to infrared applications is the insensitivity to dust, chips and cooling lubricants. It is therefore important to consider these factors during the design stage of the implementation when using infrared data transmission systems.

Because sensor-integrated tool holders are primarily located within the working space of a machining center, it is beneficial to implement the infrared data transmission unit into the machining spindle itself. In order to support an automatic tool changing system, machining spindle shafts generally hold a clamping system within their center. Thus, in most cases it is not possible to place the transceiver modules on the center line of the spindle shaft (Fig. 13, top). Due to an internal motor, the cross section of direct driven motor spindles is larger than in belt-driven spindles. This allows the IrDA transceiver modules to be built into the rotating spindle shaft in a radial orientation (Fig. 13, bottom left). To achieve maximum optical overlapping, the stationary transceiver module is located in the corner of the housing (cf. Fig. 10).

In belt-driven spindles with a smaller cross section (low optical overlapping in radial orientation), it is preferable to arrange the IrDA transceiver modules with an axial offset at the surface shell between both bearings (Fig. 13, bottom right). Due to the *large* distance between the bearings (compared to the radial implementation space), optical overlapping can be increased.

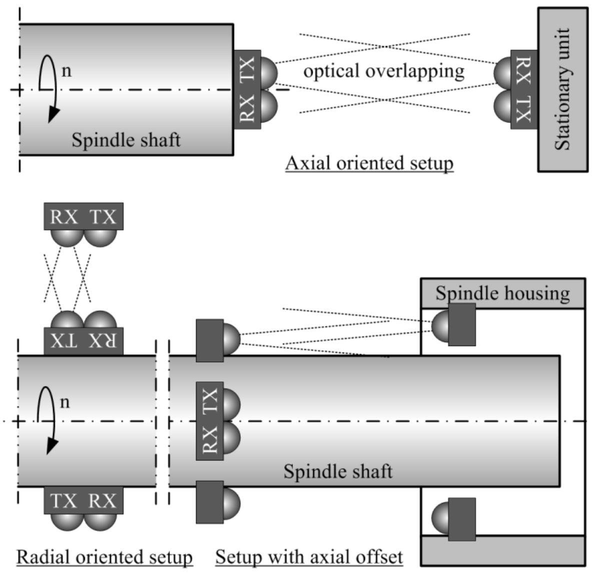

Fig. 13: Concepts for the implementation of IrDA data transmission transceivers into machining spindles

5. Conclusion

High performance cutting is characterized by a high cutting speed and a high feed speed. This leads to higher excitation frequencies, which have to be considered during the selection of an appropriate monitoring system. Particualry when processing workpieces with a high weight (low eigenfrequency), it is beneficial to use sensor-integrated machining spindles or tool holders. In order to provide fast and reliable data transmission, a real-time monitoring system based on infrared data transmission was developed. The contact-less and continuously transmitting unit is based on the IrDA VFIR protocol. Furthermore, the microcontroller within the stationary unit of the monitoring system was optimized to carry out all required calculations (calibration, compensation, filter, pattern recognition). The whole system has a data transmission rate of 4.1 Mbit/s, with a maximum reaction time of 7.14 ms. Additionally, a sampling rate of four sensor signals of 42.5 kHz was achieved.

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