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Low power sensor node with photovoltaic power supply for radio-based process monitoring

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Abstract

This paper presents the idea of improving existing process monitoring systems for drilling, milling or threading by employing a novel communication technology as well as energy harvesting methods. An overview of the system including sensor node, energy supply and communication technology is given. The radio transmission methods are investigated in terms of power consumption in order to define requirements for the power supply. Fundamental measurements to characterize the behavior of different types of solar cells under artificial light are performed. Based on the results, two designs of sensor node prototypes are presented. The optical power supply and the energy harvesting system for the demonstrators are shown in detail.

Keywords: process monitoring; 24 GHz RFID; wireless sensor node; RF communication; optical power supply; energy harvesting

1. Introduction

Competitive manufacturing processes, especially against the background of Industry 4.0, require optimum utilization of machines and tools as well as early fault detection and quality assurance through application-specific monitoring systems. Such systems are employed for cutting machine tools to monitor rotating and rigid tools during

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thread cutting, drilling or milling. Currently these systems employ inductive couplings for wireless data and energy transmission or active radio systems (868 MHz or 2.45 GHz) in combination with a rechargeable battery. There are no systems available on the market that simultaneously meet the industrial requirements such as small dimensions, high data rate (at least 128 kbit/s) and transmission range (at least 0.5m), usage time of at least 12 hours, worldwide radio licensing and robust integration.

In order to solve the run-time problems of battery-powered systems while simultaneously improving the data transmission performance, the Institute of Transport and Automation Technology and the Institute of Microwave and Wireless Systems together with MARPOSS Monitoring Solutions GmbH, a world leader in process monitoring for machine tools, have started a cooperation. The aim of the work is to further develop the solar cell-powered 24 GHz communication system developed in CRC 653 for stationary workpieces [1] into rotating applications like threading or drilling processes. The sensor node operates in a license-free frequency ISM (Industrial, Scientific and Medical) band and uses a connection based on backscatter modulation of a radio signal from a read/write device, which minimizes the energy consumption on the sensor node side for data transmission. With the help of the integrated solar cell in conjunction with an external light source, the sensor node can operate irrespective of the prevailing lighting conditions. Using advanced energy harvesting methods and low power components the sensor node enables self-sufficient radio-based process monitoring. In order to ensure robust operation, an industrial read/write device and an extended communication protocol, which allows the parallel operation of at least four sensor nodes, are required. The functional principle of the system is shown in Fig.1.

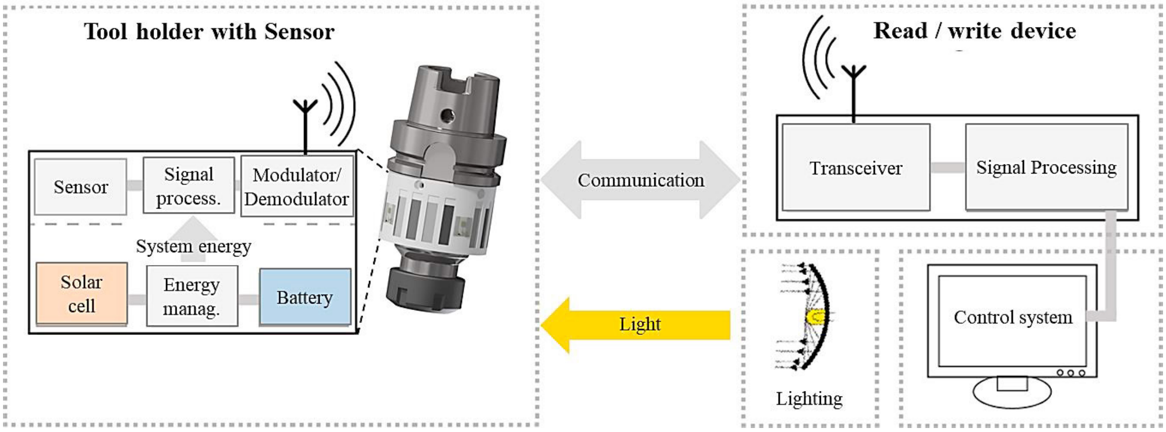

Fig. 1. Functional principle of the low power sensor node with photovoltaic power supply

2. Energy Analysis

2.1. Communication System

To achieve autonomous operation of the sensor node, investigations of the energy balance are fundamental. The actual system offered by MARPOSS Monitoring Solutions GmbH uses Wi-Fi for wireless communication between the rotating sensor and the control system. This radio link offers a high data rate and a robust connection but is disadvantageous in terms of energy efficiency. Other elements of the sensor node system like strain sensors and controllers have a smaller impact compared to the energy consumption of the Wi-Fi module. Therefore, the energy consumption of the communication system is in focus.

The choice of the radio transmission method depends on the application of the sensor node, because the application determines the conditions for the data transmission. In this case, the sensor node will be applied to a rotating tool holder to monitor the tool state. For example for a quick response on fault detection during threading, four sensors (16 bit per sensor) have to be sampled with 2 kHz resulting to a data rate of 128 kbit/s. A distance of 0.5 m for wireless transfer is sufficient. The delay time (latency) from sampling inside the sensor to receiving at the reader should be lower than one millisecond. Nevertheless, a key performance indicator is the small energy consumption of the radio module. The miniature dimensions of the sensor node limit the size of the battery and the solar cell area. For long runtimes without battery charging, the energy consumption must be as small as possible.

The current consumption of a typical Wi-Fi module will be discussed in the following. With a Rohde & Schwarz Oscilloscope (RTO2014) and a current probe (RT-ZC30) the Wi-Fi module CC3200 from Texas Instruments is measured in the time domain during different operation conditions. Our investigations show, that the current consumption is strongly dependent on the method, how the Wi-Fi standard is used for data transmission. In particular, especially the packet size and the repetition rate of the packets have an impact on the average power consumption.

Fig. 2a shows the Wi-Fi module current versus time (module voltage is 3.3 V) while sending simple UDP packets with two different repetition times. The very high current peaks (up to 300 mA) occur when sending out the packets; the lower current values represent the idle or sleep state of the module. In the first measurement (blue trace) 50 Byte packets are sent with a period of 40 ms. After sending out a packet, the module returns to idle state and consumes around 60 mA. In this constellation a mean current of 63.3 mA can be detected. In comparison, a measurement with 1500 Byte packets and a repetition time of 80 ms is presented (black trace). It is obvious, that the current in idle state is significantly lower with 17.4 mA. This results from the sleep state of the modules [2]. For long idle times (around >50 ms), the module switches in a sleep state. Many components in the module will be turned off for power saving. Because of a needed start-up time, this cannot be done for short idle times. While the packet size has nearly no influence on the mean current, an increased period between sending the packets leads to a downfall in the mean current due to the explained sleep mode. From this behavior, it can be deduced that an efficient data transfer will be reached with large packets and a large repetition time.

The results are in contrast to the demand of the monitoring application, which is an energy efficient data transfer with preferably no latency. Also, the high data rate which is possible with the Wi-Fi standard is not needed. The standard also includes a complex protocol with many layers on top of the physical layer, shown in Fig. 2b, that is not tailored to the application. The processing of a large overhead compared to the amount of data reduces latency and energy efficiency.

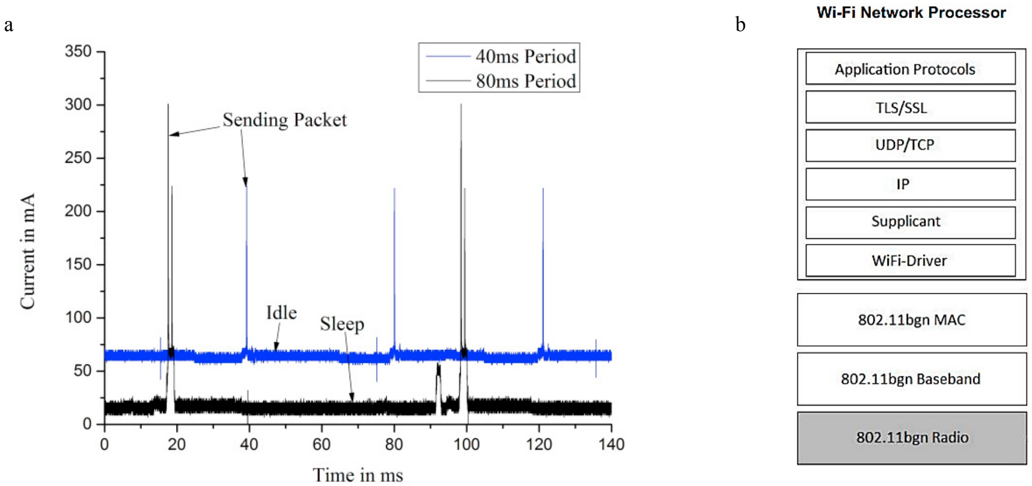

Fig. 2. (a) Current consumption versus time for 40 ms and for 80 ms packet repetition time; (b) Block diagram of the Wi-Fi network processor [3]

A specialized data transfer solution for this application can drastically reduce the energy consumption of the wireless module. In contrast to the Wi-Fi solution which works with an active radio transmitter on the sensor side, very low energy consumption would be reached with a passive wireless module on the sensor node, which communicates with backscatter modulation. During the data transfer from the sensor to the control system the reader sends an unmodulated radio wave to the sensor node. The sensor node reflects the received signal under control of the sensor data stream; typically amplitude shift keying (ASK) is used for this purpose. The energy needed by the sensor node for backscatter modulation almost goes to zero; a simple transistor switch is sufficient.

Based on the achievements of CRC 653 [4] a backscatter modulation at 24 GHz for wireless data transfer will be developed. This transponder uses a transistor (Avago VMMK-1225) for modulating the reflection coefficient of the antenna and therefore needs an energy of approximately 280 µW. Fig. 3a shows the time varying current consumption (blue curve) of the whole sensor node with a 2 V power supply for a complete sensor value request from the reader [4]. A detailed analysis of the time dependent current consumption gives insight into power consumption of the different components of the sensor node. In step 1, the reader transmits a continuous wave, but no data. In this time, the transponder waits in sleep mode with a very low current of ~30 µA. If the reader sends a request (step 2) by modulating the continuous wave, the output voltage of the transponders demodulator is used to receive and to decode the data in the microcontroller. The received data is processed and the A/D-converter for sensor measurements is activated in step 3. The transponder sends a response by switching the load impedance of the sensor antenna between two states (step 4). Finally, the transponder goes back to sleep mode and waits for the next request from reader.

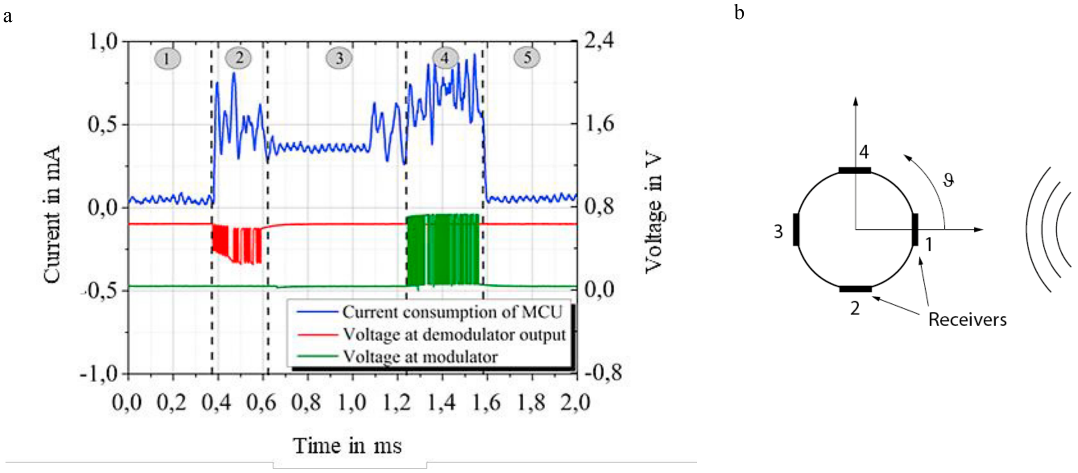

Fig. 3. (a) Current consumption of the 24 GHz-transponder with backscatter modulation; (b) Top view of the rotating tool holder equipped with four combined antennas

In terms of power consumptions the backscatter modulation promises great advantages. Combined with the sensors and the microcontroller for the desired application, a maximum average energy consumption of around 10 mW is expected. The high saving is reached mainly due to the data transfer optimization. On the other hand, new challenges arise. While Wi-Fi operates with transmitter power of up to 100 mW and has a receiver sensitivity of -90 dBm or better, the possible communication distance between transmitter and receiver is large. In combination with reflections on machine walls etc. there are no considerable problems due to shading of the antenna from the tool holder itself.

With the backscatter modulation at 24 GHz only a short range transmission of about 0.5 m is reachable with standard receiver topologies. This would be sufficient for a typical line of sight communication link, but in our application with a rotating machine tool holder, shading effects lead to severe problems with the stability of the communication. To overcome these problems several solutions are currently under investigation. For example, a diversity receiver with a baseband combining to prevent shading and fading effects is used as well as new receiver concepts with improved sensitivity. Fig. 3b shows the top view of a rotating tool holder, equipped with a sensor node with four antennas combined in the baseband.

2.2. Optical power supply

To select the solar cells to be employed on the sensor node, an intensive market survey of solar cells is conducted. Samples of all available types of solar cells are acquired to test their performance under artificial light conditions. The following solar cell materials are available on the market (c.f. [5]): Cadmium telluride (CdTe), copper indium gallium selenide (CIS), mono crystalline silicon (monoSi), poly crystalline silicon (polySi), micro crystalline silicon (µSi) and amorphous silicon, with one type designed for indoor use (aSi_In) and another for outdoor use (aSi_Out). Also tested are triple junction cells on germanium substrate (triple). The solar cell modules differentiate in the material employed as well as in their dimensions.

During the tests LED modules varying in color temperature between 2700 K and 6000 K are used to provide illumination. The decision to employ LEDs is based on their dominant application as illumination of the working space of machine tools. Figures 4a and 4b show the results for the power output of the listed solar cell types under different levels of illuminance from a LED module with a color temperature of 6000 K. The measurement results are obtained by a source measure unit Keysight B2902A. Due to the different dimensions of the tested cells the power output is normalized to microwatts per square centimeter solar cell aperture (µW/cm²).

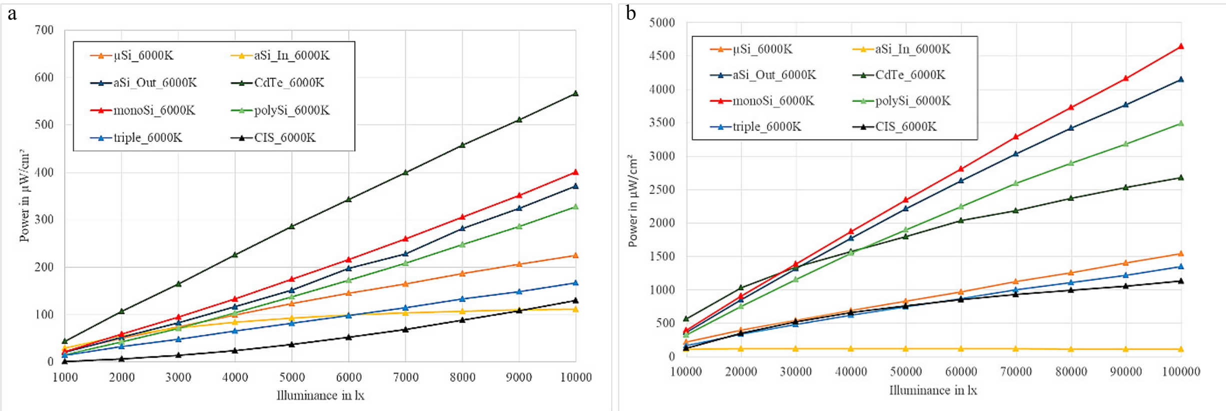

Fig. 4. (a) Generated solar cell power for illuminance 1000 lx - 10.000 lx; (b) Generated solar cell power for 10.000 - 100.000 lx

The illuminance levels shown in Fig. 4a can be realized by the built in illumination of the machine tool under ideal conditions. However, even with large areas of solar cells the output power is too low to reach 10 mW desired for the final prototype using backscatter modulation and certainly too low to reach 100 mW needed for the current prototype using Wi-Fi communication. Therefore an additional light source has to be brought in to provide higher illuminance levels. Monocrystalline solar cells perform best under these conditions (c.f. Fig. 4b). The monocrystalline solar cells investigated in the characterization test are made by the company IXYS (IXOLAR KXOB22-04X3) [6]. Taking into account the power demands of the different communication technologies, the solar cell area needed to power the prototypes is calculated based on the characterization results. The Wi-Fi solution needs 110 cm² with an illuminance of 20.000 lx and 26 cm² with 80.000 lx while the backscatter solution only needs 11 cm² or 2.6 cm² respectively.

3. Development of the sensor node

3.1. Design Concept

Regarding the communication the former developed backscatter modulation of the sensor node wireless connection is utilized, instead of using an active modulation. Thus, the current consumption of the sensor node is essentially determined by the sensors with its A/D-converter and the sequence control by the microcontroller. The small antenna dimensions in this frequency range also facilitate integration into the tool holder. Due to the rotation of the sensor node and the low dynamic range of a backscatter modulated communication system, fluctuating channel characteristics or a cyclically interrupted radio link is to be expected. However, since the sensor node rotates about an axis, the fluctuations are periodically recurring and thus predictable. Consequently, measurable channel information can be used to optimally utilize the transmission channel. Therefore the communication protocol has to be adapted. Furthermore, the simultaneous use of multiple sensor nodes is currently not provided, so the 24 GHz communication system must be extended for parallel operation. With a code division multiple access (CDMA) by using spreading codes on the sensor node, a parallel use of multiple sensor nodes is under investigation.

In order to avoid the disadvantages of inductively fed or battery operated systems, a hybrid energy supply concept based on a photovoltaic system will be developed and implemented [7]. According to Fig. 1, solar cells are used for power generation in conjunction with an energy storage and an energy management system. Critical selection criteria for the solar cells are the available dimensions and absorption spectra as well as efficiencies and ultimately the price. In order to achieve a maximum energy yield, the rotor surface in the tool holder should be utilized as large as possible. Due to geometric restrictions of the rotor (curved surface, dimensions) several solar cells must be applied to the rotor and combined by circuit engineering measures to form a solar module. An external light source makes it comparatively easy to control the energy supply in all operating states. Different variants of light sources are investigated as the place of application and the type of artificial lighting. Nonetheless, due to the rotation of the sensor node or other shadowing, there is the risk that the solar module cannot guarantee a stable energy supply. With the help of energy storage devices, these periods of time can be bridged; supercapacitors or accumulators can be used for this purpose. Depending on the size of the solar module and the energy requirements of the sensors, the best solution or combination can be found for the application. Furthermore, an energy management system is constructed, which takes over the power adjustment, the DC voltage conversion in the correct voltage range, the charge and discharge control of the energy storage and the control (on / off) of the sensor node at critical voltage. Modern Energy Harvesting ICs include the necessary features such as maximum power point tracking (MPPT), low quiescent current, DC-DC conversion, low input voltage range, and battery charging and protection.

3.2. Demonstrators

Taking into account the considerations mentioned before, a prototype design of the sensor module is created. Fig. 5a shows the sensor module fitted to a HSK63 tool holder. The module consists of a housing which contains the strain sensors with the corresponding electronics, as well as the communication and energy management circuits. The outside of the housing features four antennas which are distributed symmetrically around the perimeter. Symmetrical distribution should cause continuous connection between the sensor module and the read/write unit also during rotation of the system. Also attached to the outside of the housing are the solar cells for energy harvesting. Due to the limited space on the tool holder and the typically prevailing lighting conditions inside of a machine tool, an additional light source has to be installed to facilitate the generation of sufficient energy to power the sensor module. The prototype depicted in Fig. 5a features 16 IXYS solar cells on its outside. With dimensions of 22 mm x 6 mm for one cell, these make up for a combined solar cell area of 21 cm². This area generates 19 mW for 20.000 lx and 72 mW for 80.000 lx, which is sufficient to power the backscatter modulation based solution.

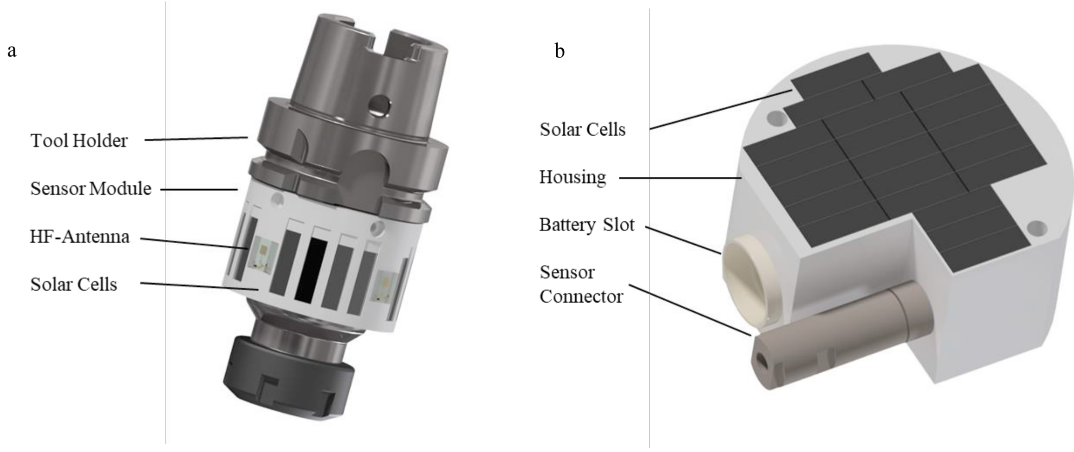

Fig. 5. (a) Prototype design for rotating applications; (b) Prototype design for stationary and oscillating applications

Though, there is not enough power generated to supply the Wi-Fi based solution, which demands 100 mW. Therefore at the current stage of the research an intermediate prototype is set up (c.f. Fig. 5b). It is based on a stationary sensor module developed by MARPOSS. 21 IXYS cells can be fitted to the surface of the prototypes housing, adding up to 27.7 cm². According to fig. 4b the monocrystalline solar cells produce 3.8 mW/cm² for 80.000 lx. That means 80.000 lx are needed to enable the 21 cells to generate 100 mW for powering the prototype with Wi-Fi communication.

The prototype is used to concentrate on the task of energy harvesting by the solar cells under artificial light while using the existing communication technology. The existing battery based power supply remains functional to back up the photovoltaic power supply. In the current design the Texas Instruments bq25570 energy harvesting IC manages the power generated by the solar cells to supply the designed system [8]. The bq25570 device is specifically designed to efficiently extract microwatts to milliwatts of power generated from a variety of high output impedance DC sources like photovoltaic systems. The battery management features ensure that a rechargeable battery is not overcharged or depleted beyond safe limits by the system load. In addition to the highly efficient boosting charger, the bq25570 integrates a nano-power buck converter for providing a second power rail to the sensor node system.

4. Conclusion

This paper presents the concept for a low power sensor node with photovoltaic power supply for radio-based process monitoring. The planned use of a backscatter modulation with an adapted protocol for wireless data transfer was justified. Demonstrated by power consumption measurements, the Wi-Fi standard turns out to be unsuitable for low latency low power data transmission. The backscatter principle represents great potential for energy-saving operation with low latency.

The evaluation of available solar cells in terms of power generation results to values in the single-digit milliwatt range with typical working space illumination inside of a machine tool. An additional light source is necessary to provide illuminance levels sufficient for generating 10 to 100 mW, which are needed for powering the planned demonstrators.

The designs of two different demonstrators are proposed. The intended final prototype working with backscatter modulation with its applied solar cells and antenna system is presented. For investigations on the energy harvesting system, an intermediate prototype based on existing Wi-Fi communication is set up. It contains a set of solar cells, an energy management with a battery and a Wi-Fi module for wireless data transfer. The power supply was examined on this prototype, which results to the need of a powerful light source to deliver 80.000 lx of illuminance. This enables the solar cells to generate sufficient power for constant operation of the system.

Acknowledgements

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