Autarkic Monitoring with Bluetooth Low Energy (BLE)

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Abstract:

The concept and realization of an autonomous measurement system is developed to provide an easy-to-implement monitoring solution for vibrating machines. The system is optimized for low power consumption. It works completely wirelessly. An inductive harvester is used to provide the required energy by energy harvesting directly from the vibration. The measured data is transmitted wirelessly using Bluetooth Low Energy (BLE). This enables a smartphone or tablet to be used to display the measurement results. A prototype has been developed to prove the system functionality in real-world applications. Experiments with the prototype also show the challenges and limits of using an autarkic system for industrial monitoring applications.

Key words: Autonomous measurement system, condition monitoring, energy harvesting, Bluetooth Low Energy (BLE).

Introduction

Permanent condition monitoring allows determining the status of production equipment during operation. It helps to avoid downtime and prevent consequential damage. Data of production facilities or production processes are evaluated at regular intervals or continuously. The data can be represented by oscillations, vibrations, positions, times, temperatures or other physical measurements.

Monitoring solutions for industrial use need appropriate measuring equipment and measuring procedures, easy-to-implement systems as well as reliable communications. A challenge is the collection of the acquired data. Beside choosing and installing the right sensor, it is necessary to wire the measuring points in the production line. Not all positions and components are easily accessible using a cable. I.e. measuring positions on moving parts increase the risk of a cable break. In particular, for the retrofitting of existing facilities, this is can be a challenge.

Concept

The basic idea is to provide an autarkic system that works completely wirelessly using ambient energy. In most industrial applications vibration can be used to harvest energy for an autarkic embedded system. The harvester can be mounted to existing equipment just by fixing it to the housing. The system communicates using Bluetooth 4.0. This allows using mobile devices for human machine interface as well as fixed equipment.

System Design

The autarkic system contains of an energy harvester, energy storage, voltage booster, microcontroller and radio as well as one or more sensors. Fig. 1 shows the block diagram of the system.

The energy required is generated by energy harvesting directly from the vibration using an inductive harvester. When enough power is collected, sensor data are acquired and the microcontroller does simple calculations to reduce the amount of data. The results are transmitted using Bluetooth Low Energy (BLE). For visualization a standard BLE-enabled smartphone or tablet can be used as well as any other BLE enabled device.
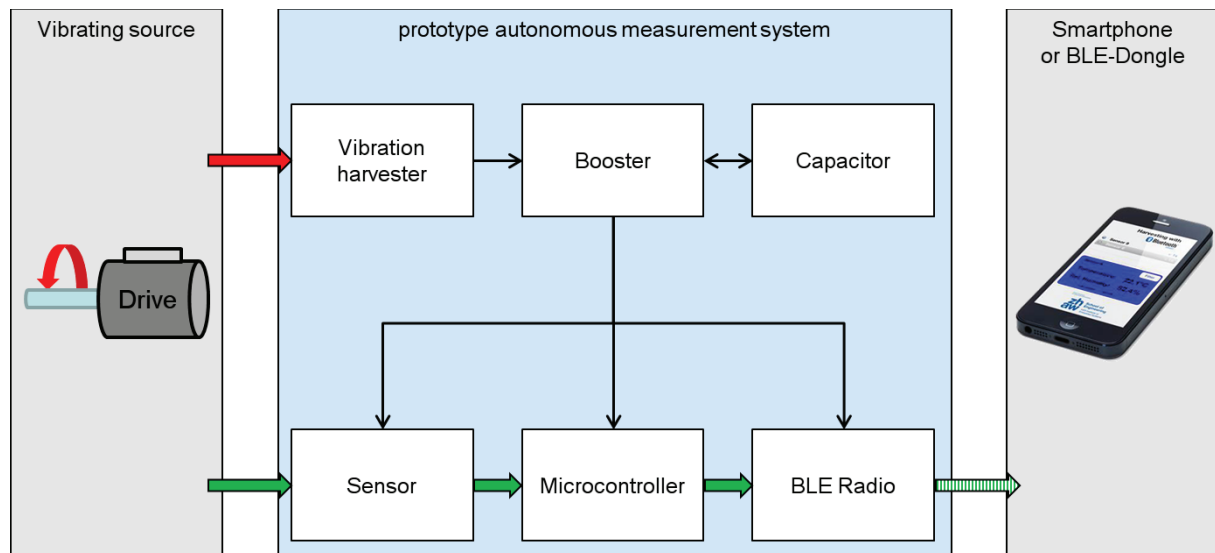
Fig. 1   System Block Diagram

Energy Harvesting

Power supply is realized using a harvester prototype working according inductive principle [1]. The harvester is operated in resonance to work in most effective range. Therefore, the resonance frequency of the harvester has been tuned to the vibrations of the system. The vibration frequency of the setup used has been figured out at 15.1 Hz.

The maximum output peak voltage of the harvester is measured at 1.2 V. That is not sufficient to operate the embedded system. Therefore a voltage booster is needed to boost the voltage up to a level of 3 V. The prototype uses a Texas Instruments booster type bq25504 [2]. It operates at an input voltage between 330 mV and 3 V using two boost modes with different efficiency. With an input of 1.2 V it works already in the high efficient boost mode. The output voltage is set to 3.054 V. The booster provides a VBAT_OK signal for power management based on an upper and an lower threshold. The signal is set at a defined voltage threshold of 2.9 V and it is cleared at 2.62 V.

The energy storage is realized by an electrolytic capacitor. The capacity determines the energy available for the transmission process. For the system considered here, it has been dimensioned to 820 µF.

Bluetooth Low Energy Data Transmission

For data transmission Bluetooth Low Energy (BLE) has been chosen. Advantages are the low energy consumption and the availability of mobile and fixed devices for receiving data. As radio an EM 9301 [3] has been selected. The system uses BLE in advertising mode, so no connection has to be established. On one hand sending data is possible in direction of the receiving device only. On the other hand the data transmission has been realized ultra-low power. To increase the probability that a data packet arrives at the receiver, it is transmitted twice. One transmission cycle includes two data packages.

Experimental Set-Up

For investigating the behavior of the system an experimental set-up has been developed (Fig. 2). It consists of the autarkic embedded system described above and a mechanical test bed. The mechanical structure is built by a drive with a variable load. A smartphone with Bluetooth 4.0 is used as receiver.

Fig. 2   Experimental Set-Up

Mechanical Set-Up

The mechanical test bed is used to generate vibrations. It represents an industrial drive or other vibrating equipment. The mechanical part has been designed to change the system

behavior in different matter. In particular the frequency and the intensity of vibrations are subject of variations. Thus it allows investigation of the properties for monitoring application under different conditions. A DC-machine is used as drive. Rotation speed and thus frequency of vibrations can be infinitely adjusted by changing voltage of the DC power supply.
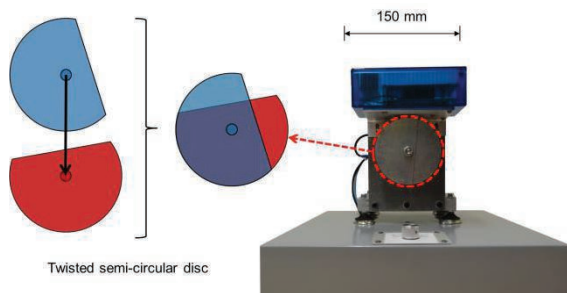

Fig. 3   Variable imbalance using two semi-circular discs

The load is realized using two semi-circular discs coupled to the drive (Fig. 3). They can be twisted to each other. This construction works as an adjustable unbalanced mass. In rotation this results in variable vibration amplitude.

Using this mechanical set-up the mechanical vibrations in terms of intensity and frequency can be varied continuously over a wide range. This allows simulating the vibration characteristics of various actuators or machines. Operating at amplitude of 0.14 g the system vibrates constantly (Fig. 4). In the frequency spectrum a strong peak can be recognized at a frequency of 15.1 Hz (Fig. 5).
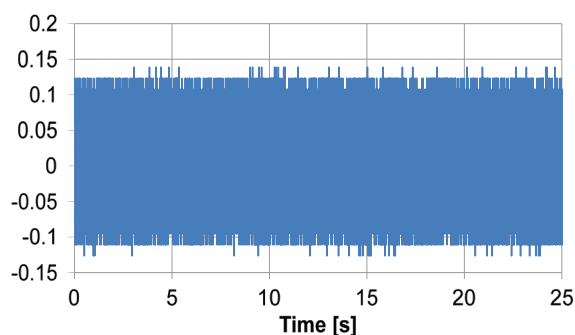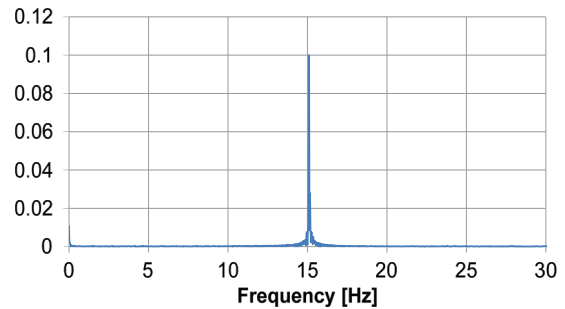

Fig. 4   Vibration vs time

Fig. 5   Vibration vs. frequency

System Running

The harvester is directly connected to the housing of the drive. It harvests the vibrating energy and charges the capacitor permanently. When the capacitor is full and the upper threshold is reached, the VBAT_OK signal indicates that sufficient power is available for a data transmission. The microcontroller is activated, the measurement is done and the measured data is transmitted. During transmission the energy stored in the capacitor drops below the defined lower threshold. After completing the transmission the embedded system is shut down again. Now the system is waiting in standby mode for the next start signal. This cycle repeats periodically.

Energy Balance

For analyzing the system energy balance, measurements were done with a DC power analyzer type Keysight Technologies N6705B [4]. To characterize the energy harvesting the output power of the booster was measured without connecting the power consumption side. The power consumption is recorded at the input without use of the energy harvesting side.

Energy Harvesting

Main parameters for the energy harvesting are vibration frequency and amplitude. Thus both parameters were varied. The frequency is changed by adjusting the rotation speed of the drive. It was set in the range of +/- 5 Hz around the resonance frequency. The amplitude is changed by twisting the two semi-circular discs. Different settings were adjusted and the resulting amplitude has been measured. At low vibration intensity an acceleration of 0.07 g is measured. The high amplitude is measured at 0.3 g and the middle amplitude at 0.14 g.

The output power is plotted in Fig. 6 as a function of frequency for different amplitudes. Operating in resonance, the harvester generates a maximum power of about 1700 μW. The bandwidth for the mechanical

oscillation is small. A deviation of the resonance frequency more than 0.5 Hz results in a power drop. For 2/3 of maximum power the bandwidth is measured at 1.92 Hz.

The measurements demonstrate that the power generated is highly depending on the frequency deviation. The harvester has to be tuned to the mechanical resonance frequency. Due to the small bandwidth for the frequency it must not vary more than 1 Hz. When the frequency gets out of range the power drops immediately. This results in insufficient output for loading the capacitor. The system would never start up.
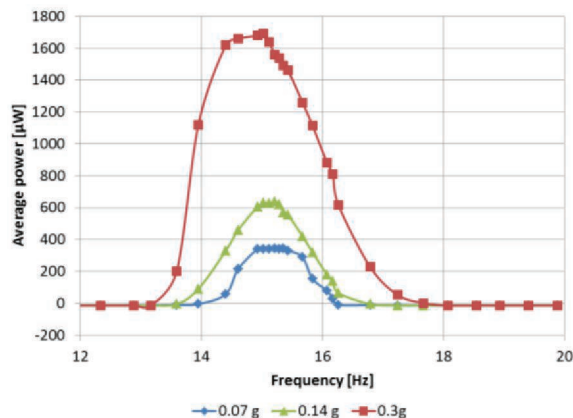

Fig. 6   Output power vs. frequency

Also vibration intensity has an effect on power collected. But it is also influencing the bandwidth for resonance frequency. Reduced vibration results in a decrease of power. Also the bandwidth decreases.

For monitoring applications there is a need of reliable functionality. Thus the energy harvesting should be dimensioned with some buffer. This means buffer for peak power as well as buffer for bandwidth.

The need to tune the harvester to resonance frequency is a limit for a real life application. The Development of self-tuning harvesters [5], [6] could enlarge the range of applications.

Power Consumption

The system initializes and starts measuring and transmitting data as soon as enough power is available.

For each transmission the system wakes up and gets initialized. As soon as the system is ready, the packet with payload data is sent twice. As soon as data transmission is completed, the system is disconnected from the power supply.   The complete transmission

process needs an energy amount of about 725 µWs including initialization.

Sending Intervals

Monitoring applications require reliable data acquisition in periodical time intervals. Thus the number of transmissions during a time period is of major interest.

A maximum number of transmissions during a time period can be expected operating the harvester in resonance frequency. At high vibration amplitude the provided power of about 1700 µW allows in theory to repeat a complete transmission every 400 milliseconds. Reducing the amplitude to low setting, the power output drops to 340 µW. In theory a maximum transmission frequency of around 2 seconds is to be expected. This numbers have been reached also in practical experiments.

In the application field of industrial monitoring intervals for sending data could be enlarged. This reduces the energy needed per time while the energy supplied during a time period is equal to the energy harvested in the experiments above (Fig. 6). The reduced energy consumption results in an increasing bandwidth for the resonance frequency. This can be used to increase the system stability against frequency deviations. A change of the interval from 15 to 60 seconds results in higher bandwidth of resonance frequency (Fig. 7).
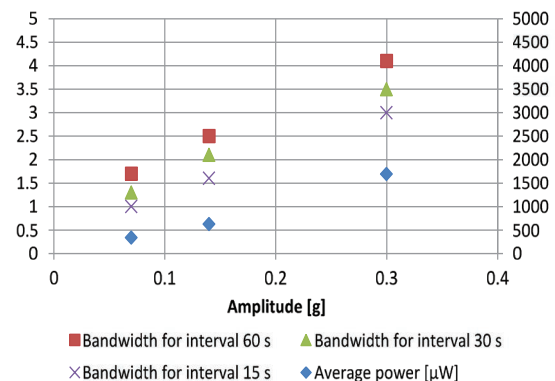

Fig. 7 Power generated and maximum vibration bandwidth

Data Visualization

The data sent can be received by all kinds of devices that are enabled for Bluetooth Low Energy. Beside permanent installed devices for data collection mobile devices can be used. This allows realizing an ad hoc data collection for service or maintenance as well as for machine operators. The settings used in the

experimental set-up allow receiving the signal in a distance of up to 50 m. But in real industrial applications this would be limited by the environment.

Conclusion

The combination of energy harvesting with Bluetooth Low Energy is very interesting for monitoring applications. Tests with the prototype prove the suitability of the concept. More than sufficient energy has been collected for data acquisition and data transmission. The experiments have shown that several measurements can be performed in a minute. This includes sending the results to the evaluation system using BLE. The minimum time between two received packages is mainly depending on the energy harvested. If the harvester is operated at its resonance frequency, time intervals can be less than one second. Using BLE for wireless connection offers the possibility to use simple devices as smartphones or tablets for visualization. There is also the possibility to integrate such a system in an existing infrastructure.

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