DOI 10.5162/iCCC2024/P2

VibroMote: Energy efficient Vibration Monitoring for Railway tracks and Bridges

Navya Sneha Chatharajupalli [1], Randolf Rotta[1] and Jörg Nolte[1]
[1] BTU Cottbus-Senftenberg, Cottbus, Germany
chathara@b-tu.de,rottaran@b-tu.de

Summary: Filtering, storing, and transmitting measurements of high-resolution sensors within a limited energy budget is challenging. For instance, a 3-axis MEMS acceleration sensor for structural condition monitoring and predictive maintenance generates up to 160 kB/s at a sampling rate of 26.6 kHz. This paper discusses the design space with focus on solar harvesting solutions. VibroMote is an energy efficient sensor node that combines a multi-radio micro-controller, an ultra-low power co-processor with persistent memory, a solar harvester, and multiple energy storage options. This enables prototyping of solar-powered long-term data acquisition, in-node processing, and wireless networking for high-resolution sensors.

Keywords: Structural Monitoring, Solar Harvesting, Wireless Sensor Networks, Vibration Monitoring, Data Analysis

Introduction

Solar Harvesting techniques are widespread in the area of Wireless Sensor Networks (WSN). In our application domain, which is predictive maintenance of railway tracks and bridges, we need sensor nodes that have long life-time and require little maintenance. Based on a previous prototype, the sensor and microcontroller consume around 1 mW for deep sleep waiting for vibration events, 5 mW for data recording during radio sleep and 0.1 to 2 mWh per MB of transmitted data. Thus, the daily energy consumption would range from 24 mWh for full sleep to 120 mWh for continuous recording and processing, and additional energy would be needed for maintaining network connectivity and transmitting interesting recordings.

For this we investigated various energy harvesting and storage technologies. Harvesting can be based on photovoltaic, thermal, vibration, or radio-frequency. Of these, photovoltaic harvesting is the easiest to scale to above requirements.

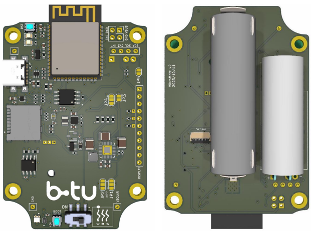

Fig. 1: VibroMote: Front and Back View

Related Work

The motivation behind this work is to develop a battery-free solar harvesting based sensor node. The battery state of charge approximation is very crucial if we wanted to extend the lifetime of the sensor nodes, the various ways to model the same are explained in [1], the approximation models are developed based on the voltages and drain currents and has an accuracy of 95% even under varying operating conditions. Even with the approximations one can only assume the battery discharge rate but not the decay of the battery.

For such scenarios we look for the replacement such as supercapacitors, in [2] they made analysis of the charging and discharging rate of the supercapacitor that can be used for indoor photovoltaic energy harvesting module. The authors conclusively proved that the leakage current in supercapacitor was low compared to the batteries and can be used as alternative source of energy for wireless sensor nodes.

For our *VibroMote* we did an extensive research on finding the design that have the capability to switch between battery free mode to battery based mode. For the battery free mode we have used the Li-ion capacitor as the source of storage since they have very low discharging rate compared to the commercially available Li-ion and LiFePo4 cells.

The self discharge of Li-ion capacitor is quite low compared to that of a supercapacitor. In [3], the authors explained the various reasons for the discharge of the capacitor and gave an overview about how the discharge happen and how charge redistribution works. They proved that the voltage drops are not effected by the energy loss of the device.

In [4], the self discharge of the Li-ion capacitor proved to be high due to the positive electrode. The authors determined that after 50–100h at very high voltages the discharge rate of the Li-ion capacitor is significantly reduced, this is mainly because of the ions filling the surface of the electrode resulting in homogeneous charge distribution of the positive electrode and low leakage resistance.

The operating temperature of Li-ion capacitors plays a vital role in certain applications where there is constant change in temperatures. This was clearly evaluated in [5], where the assessment of the same at various temperatures are done and from the Nyquist plot shows that the behaviour of Li-ion capacitor varies a lot with varying temperatures.

The latest research on battery free methods was done in [6], where the evaluation of various parameters of the supercapacitor like charging and discharging rates were performed using the photovoltaic solar panels. Although the research on the Li-ion capacitor conclusively proves that it has low discharge rate than compared to the supercapacitor. So we decided to use the same for our battery free design.

VibroMote Requirements

This section summarizes the design rationale of our prototype with respect to vibration sensing, communication of measurements, and in-sensor data analysis. From this, the requirements for the energy harvesting and storage are derived.

Vibration Sensing

The interesting wavelengths for structural monitoring of bridges depend on their construction, the speed of passing trains, the train's axle distance, and the railroad cross-tie distance, for example in the range from 0.1 Hz to a few 100Hz. A shift in resonance frequencies and a shift in relative vibration amplitudes indicate problems with the bridge, for example with blocked bearings. Higher frequencies are interesting for the identification of flat spot in wheels and defects in rails and railroad switches. Thus, sensors with the lowest possible noise density, sufficiently high bandwidth, and a flat frequency response are needed. In recent years, 3-axis MEMS accelerometers became available that meet these requirements and allow to differentiate vertical, longitudinal and transverse vibrations.

For prototyping, we selected the STMicro IIS3DWB vibration sensor for its low noise density ¡110 μg/$\sqrt{\text{Hz}}$ and 6 kHz bandwidth. Its high sampling rate of 26.7 kHz is challenging as it generates 160 kByte/s that need to be stored, processed, and potentially transmitted. The current consumption during active sampling is 1.3 mA. The integrated activity detection allows to reduce the consumption and wake up the main processor. Other available sensors provide either lower noise density at a higher power consumption or more energy-efficient and AI-supported activity detection. Thus, a combination of two sensors can be interesting.

Communication of Measurement Results

Wireless communication is a key factor to reduce deployment costs. However, the actual requirements depend on the usage scenario: Alert messages when thresholds are exceeded are very small and rate but benefit from low latency. For these, sub-GHz technologies like LoRaWAN and NB-IoT are sufficient. The transmission of load statistics and selected raw data for detailed analysis requires better energy efficiency for rare but large messages. Here, LTE-M and related 5G technologies are a better fit.

The above approaches focus on communication to centralized services in the internet. However, multiple sensors are typically needed in order to monitor different parts of the bridge. Direct data exchange between the sensors enables local aggregation and analysis. This is much more energy and cost efficient than transmitting everything into the cloud. For such local communication, Bluetooth Low Energy (BLE) and Wi-Fi (IEEE 802.11) are available.

Our prototype combines BLE and Wi-Fi in order to exploit the strength of both. BLE is efficient for periodic signalling of small messages whereas the high bitrates of Wi-Fi are more efficient for the transmission of large data. Despite their energy efficiency, all above technologies consume demanding high peak currents that require care in the power supply design. For example, the ESP32 Wi-Fi radios used in our prototype need up to 350 mA during transmit.

In-Sensor Data Processing and Storage

Although all data analysis and event classification can be done directly on the sensor nodes, the aspects of interest such as thresholds and event patterns are often not known in advance. Thus, a few seconds of raw vibration data should be recorded for all vibration events, such that the collected statistics can be re-evaluated and verified later. An µSD card of 16GB capacity will suffice for 26h of vibration data.

A few 100 kB of memory would be sufficient although more memory simplifies the software prototyping: At least 32 kB memory are needed to buffer the occasional 200ms write latency of µSD cards. In order to achieve good Wi-Fi throughput around 30 kB, message buffers were needed in our experiments. The data analysis does not need to keep multiple seconds of raw data in memory by applying down-sampling to the relevant frequency range.

The sensor node's processor needs to be able to retrieve the data from the accelerometer, store it into the µSD, perform frequency analysis, pattern recognition, and Kalman-filter based integration to estimate amplitudes. In addition, statistics and raw data need to be communicated via BLE and Wi-Fi or an optional LTE-M modem. A wide range of micro-controllers such as the

STMicro STM32, Nordic nRF53, and Espressif ESP32 families meet these requirements.

Although the ESP32 family is not the most energy-efficient option, we selected the ESP32-S3 micro-processors with integrated Wi-Fi and BLE. These modules include up to 16 MB of RAM and hardware acceleration for DSP and AI algorithms. The operating voltage has to be 3.3 V and a power supply providing 500mA peak current is recommended. In order to make use of the light-sleep power mode with temporarily disabled radio, an external 32kHZ crystal is needed. This reduces the consumption to around 0.5 mA while retaining all memory contents.

The ESP32-S3 also has a deep-sleep mode with the memory powered off while a RISC-V based ultra low power (ULP) co-processor continues to interact with external devices. Unfortunately, the co-processor is too slow to handle the data output of the IIS3DWB vibration sensor.

Design of Energy Harvesting for High-Current Wireless Sensor Nodes

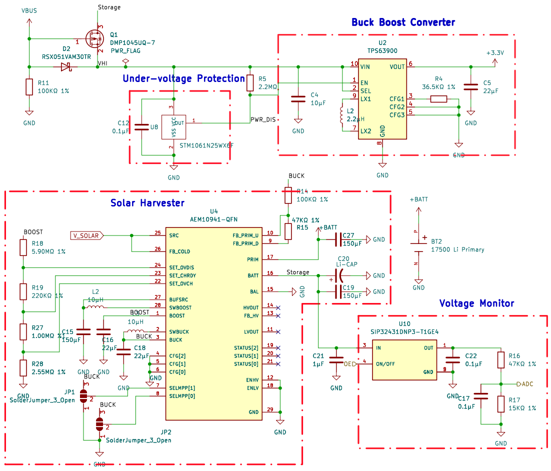

Fig. 2: Schematic of the VibroMote energy harvesting.

This section discusses our energy harvesting design to meet the requirements described in the previous section. Figure 2 shows a schematic of the respective power management circuit.

In order to transfer power from solar cells to a storage element such as a super-capacitor, a voltage converter is needed. The optimal charging current depends on the lightning condition and changes over time. Hence, energy harvesters implement a maximum power point tracking (MPPT). Respective modules are available from Texas Instruments, E-peas, and STMicro. Table 1 gives an overview of available ICs. Their main differences besides efficiency are the minimum voltage at which they begin to work, the maximum open-circuit voltage and the maximum charge current they can handle. This restricts the selection of solar cells.

Tab. 1: Comparison of available solar harvester ICs.

Name	V_{in}(V)	P_{max}(mW)	I_{max}(mA)
ADP5091	0.08 – 3.3	600	150
ADP5092	0.08 – 3.3	600	150
AEM10300	0.10 – 4.5	570	110
AEM10330	0.10 – 4.5	570	110
AEM10900	0.10 – 1.5	500	110
AEM10941	0.05 – 5.0	550	110
BQ25504	0.10 – 5.5	400	100
BQ25570	0.10 – 5.1	510	110
EM8500	0.10 – 1.8	300	10
LTC3330	3.00 – 19	475	50
LTC3331	3.00 – 19	475	50
LTC3588	2.00 – 18	450	100
MAX20800	1.50 – 18	n/a	1200
MAX20801	1.50 – 18	n/a	1200
MAX20361	0.225 – 2.50	300	715
S6AE101A	2.00 – 5.5	120	n/a
SPV1050	0.15 – 18	n/a	70

We selected the e-peas AEM10941 harvester because of its low minimum input voltage, high efficiency, and large maximum power of 550 mW. We use two Anysolar SM141K07TF solar panels connected in parallel for a combined maximum power of 430 mW. A Lithium primary cell is integrated as backup in order to provide power for basic functionality. The harvester is compatible with different types of storage elements and the respective voltage limits are configured by the resistors R18, R19, R27, R28 in Figure 2.

The AEM10941 also contains a low-voltage (i.e. 1.8V) and a high-voltage (i.e. 3.3V) regulator output. However, their peak current is limited to 80mA and, hence, insufficient for the VibroMote. The storage element can provide this current but does not match the required 3.3V. We solve this by introducing a buck/boost converter that powers the microcontroller and sensors directly from the storage element.

This external converter would continue to power the system below the storage element's cut-off voltage and damage it. With the chosen Li-ion capacitor, the converter needs to be disabled at 2.5V. The naive approach would be to use the harvester's voltage output to enabling the external converter. When the configured V_{OVDIS} over-discharge voltage is reached, the harvester disables the voltage output and hence the converter.

However, this behaviour is not desirable in combination with the backup battery. At V_{OVDIS}, the harvester charges the storage element from the backup until the charge-ready voltage V_{CHRDY} is reached and, then, activates the voltage output again. Meanwhile the microcontroller was powered down and lost network synchronization and important sensor events. Our solution uses a dedicated voltage monitor (under-voltage protection in the schematic) that disables the converter at the 2.5V cut-off voltage. The harvester's over-discharge voltage V_{OVDIS} is set higher to 2.56V such that the harvester utilizes the backup before the system has to be powered off.

It is the micro-controller's responsibility to reduce its energy consumption when the storage element is almost empty. For this purpose, the state of charge needs to be estimated. As discussed in the related work section, battery models can become quite complex while Coulomb counting accumulates measurement errors. The situation is more promising for Li-ion capacitors because their voltage has an almost linear relationship to the remaining charge. Thus, we added a voltage monitor that provides feedback to the micro-controller. It consists of a low-power high-side switch and voltage divider.

Conclusions

We designed a wireless sensor node for the structural vibration monitoring of railway tracks and bridges. The design focuses on sensors with high data rate and local communication of large datasets. In order to enable autonomous long-term operation, the sensor node integrates a solar-powered energy harvesting. The design exploits a high-capacity Li-ion capacitor in order to meet peak current demands, provide sufficient run-time, and simplifies the state of charge estimation.

The flexibility of this hardware within a wide range of applications is an interesting aspect. Furthermore, with the on-board machine-learning cores not only on ESP32 but also on the vibration sensor board makes it more feasible for bringing intelligence to device level with less power consumption.

References

[1] B. Buchli, D. Aschwanden, and J. Beutel, "Battery state-of-charge approximation for energy harvesting embedded systems," in *Wireless Sensor Networks* (P. Demeester, I. Moerman, and A. Terzis, eds.), (Berlin, Heidelberg), pp. 179–196, Springer Berlin Heidelberg, 2013.

[2] X. Yue, J. Kiely, D. Gibson, and E. M. Drakakis, "Charge-based supercapacitor storage estimation for indoor sub-mw photovoltaic energy harvesting powered wireless sensor nodes," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 3, pp. 2411–2421, 2020.

[3] A. Lewandowski, P. Jakobczyk, M. Galinski, and M. Biegun, "Self-discharge of electrochemical double layer capacitors," *Phys. Chem. Chem. Phys.*, vol. 15, pp. 8692–8699, 2013.

[4] B. Babu and A. Balducci, "Self-discharge of lithium-ion capacitors," *Journal of Power Sources Advances*, vol. 5, p. 100026, 2020.

[5] H. Gualous, G. Alcicek, Y. Diab, A. Hammar, P. Venet, K. Adams, M. Akiyama, and C. Marumo, "Lithium Ion capacitor characterization and modelling," in *ESSCAP'08**, (Rome, Italy), p. on CD, Nov. 2008.

[6] V. Boitier, B. Estibals, F. Huet, and L. Séguier, "Battery-Free Power Supply for Wireless Sensor Combining Photovoltaic Cells and Supercapacitors," *Energy and Power Engineering*, vol. 15, pp. 151–179, Mar. 2023.