LOW POWER WIRELESS TRIAXIAL VIBRATION SENSOR DESIGN - PROTOTYPE REVIEW

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Abstract: Attend a maintenance or reliability conference today and you can't fail to miss the many vendors offering wireless sensors for condition monitoring. Wireless sensor networks offer a way to expand the practice of CBM by making more condition data from more machines available for analysis. The recent advancements of MEMS accelerometers, energy harvesting techniques, and low power wireless communication facilitate the development of specialized vibration sensors for machine maintenance applications. This presentation describes a low power MEMS accelerometer based vibration sensor with energy harvesting and wireless communication capabilities.

Key words: Accelerometer; MEMS; Sensor; Vibration; Wireless; Energy harvesting; TEG; Low power

1. INTRODUCTION

The use of vibration based condition monitoring for rotating equipment is a relatively well development application, with a mature eco-system of sensor and instrumentation vendors, service providers and signal processing techniques for monitoring and diagnostics. Less well served is the emerging trend by machine makers and OEMs to instrument their own equipment, developing the components necessary for their particular machine along with new business models to service their customers. In many cases, the machines require a more specialized approach to all aspects of the system – sensor, interface, network, data processing, storage and display, with implications for the service or business model. We describe the results of an OEM program to develop a diagnostic and prognostic regime for machine faults that were previously diagnosed only by field specialists. The goal of the program is to automate the identification and diagnosis of machine faults, both old and new, with a suite of sensors envisioned to monitor aspects of the machine behavior currently not monitored.

The vibration sensor is defined to be a low-power device, with a battery that will need replacing on the order of 8 -10 years. This life span may require the sensor itself to supply at least some of its own power needs with harvested energy, potentially from more than one source. The maximum sample and transmission rate is expected to be 4 times per hour, but may often be as infrequent as once per day (depending on the measurand). The measurements will be wirelessly transmitted via Bluetooth Low-Energy (BLE) to a local 'hub' for processing with other measurands, with modest transmission distances measured in single digit meters. With the assumption that radio transmission dominates the power budget, local signal processing will be considered to reduce the amount of transmitted data, if it saves power. Research for the application reveals that vibration measurements are to be taken in all three axes of orientation in a frequency band from 10Hz to 3.5kHz.

2. SIGNAL PROCESSING DECISIONS AND BOM

After early consultations with a sensor vendor the ADXL356 by Analog Devices is evaluated, validating the sensor performance for this application. The bandwidth of the sensor output is high enough to cover the vibration frequency range of interest. The output signals are in analog format which requires an ADC with MUX to digitize the analog outputs. Due to the relatively high accelerometer output resistance, additional ADC driver circuits are implemented. Since the ADXL356 outputs are ratiometric values with respect to its analog power supply voltage, the analog power supply of the ADXL356 is used as the ADC reference voltage. Further, experiments indicate that a voltage buffer is required to drive the ADC reference input in order to avoid SNR degradation when digitizing signals with relatively high frequencies.

Another early decision made was regarding the signal processing. The design team opted to transmit time series data instead of frequency spectrum. This allows the data to be processed post transmit in a way that is not power constrained (for example in the data hub or gateway). In addition, transmitting time series data prevents information loss, whereas frequency spectral data may reduce resolution of the content.

Transmitting frequency spectral data after an FFT also doubles the sample size in order to preserve phase information, hence the FFT may not necessarily have a smaller data packet.

The first prototype was constructed with 4MB of RAM, with a controller external to the radio module for signal processing flexibility. The data acquisition design centers around the ADS8331 16b 500ksps 4/8-channel input ADC with the PIC24FV32KA302-I_SN low power 16bit microcontroller (MCU).

Due to the relatively modest transmit distances and data transmission, a TI CC2640r2 radio chip was chosen for the first prototype due to availability of modules with BLE4.2 software stacks, with relatively high data transmission rates, the SimpleLink^{TM} LaunchPad^{TM} development environment, and a migration path to radios with more memory and BLE5.0 support. The CC2640r2 is equipped with a 32-bit ARM® Cortex®-M3 processor that runs at 48 MHz.

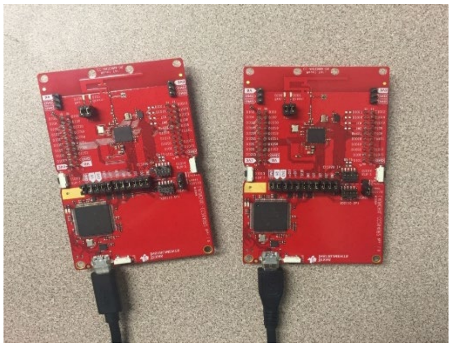

Figure 1. CC2640r2 radio modules from TI were chosen for the prototypes, which support the higher bit rates of BLE4.2. Radio modules that support BLE5.0 may be used for subsequent prototypes.

3. PROTOTYPE DESIGN

Current prototype is configured to wake up, take 512 data points at 16 Ks/s sampling rate for each x, y, z axis of orientation and immediately transmit to the BLE radio developer board, repeating the measurement and transmission cycle once per minute. For data display and evaluation, the team is using the MATLAB GUI. The prototype card size is 2.5 x 4.0 inches. Size reduction approaches to the 2nd prototype may include using the 12-bit ADC integrated in the controller. We will also probably migrate to a two card stack solution, as there is more available space in the application for height than there is footprint. Architecturally, it also makes more sense to separate the sensor plus DAQ components from the radio, making the design more modular for future modifications and component replacements.

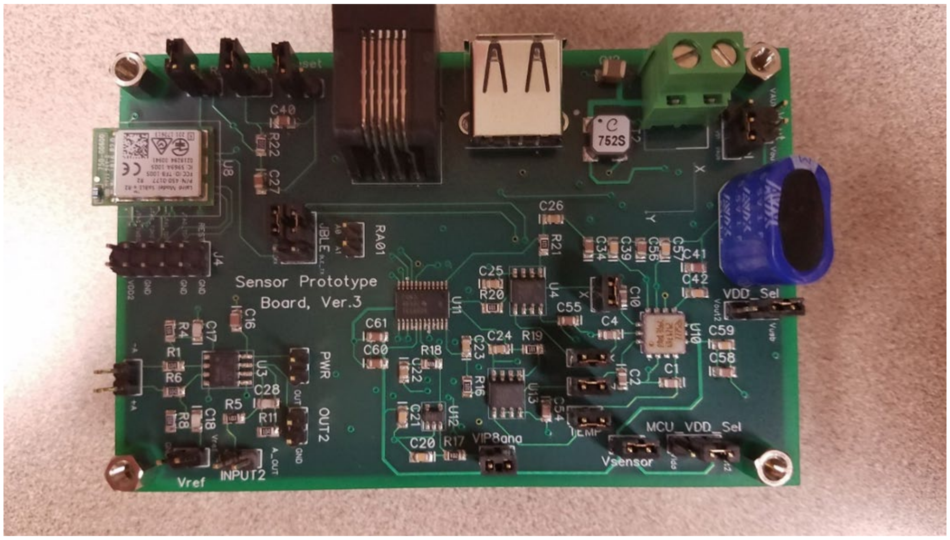

Figure 2. The first prototype, with the radio card shown upper left, the supercap at the edge on the right, and the MEMS accelerometer in the lower right.

Many of the problems encountered early in prototype development are probably common to new designs with a multiplexed sampling input (necessary for sampling the 3 outputs of the triaxial accelerometer). Prototypes were tested on a shaker table with a reference accelerometer from PCB, sampled at 30kHz.

4. LIMITATIONS ON SAMPLE RATE

Early designs ran into issues achieving the target sample rate, leading to erroneous samples. Some of the more mundane problems to track down included firmware bugs (thought to be internal CLK frequency inaccuracy).

Analysis of the timing signals reveals that, although designed to sample at 16Ks/s, the system was actually sampling at 13.4 Ks/s instead. The first suspect was an inaccurate RC oscillator built in to the microcontroller used to set the timing, resulting in the unexpected data capture rate, but the error was tracked down to a firmware bug.

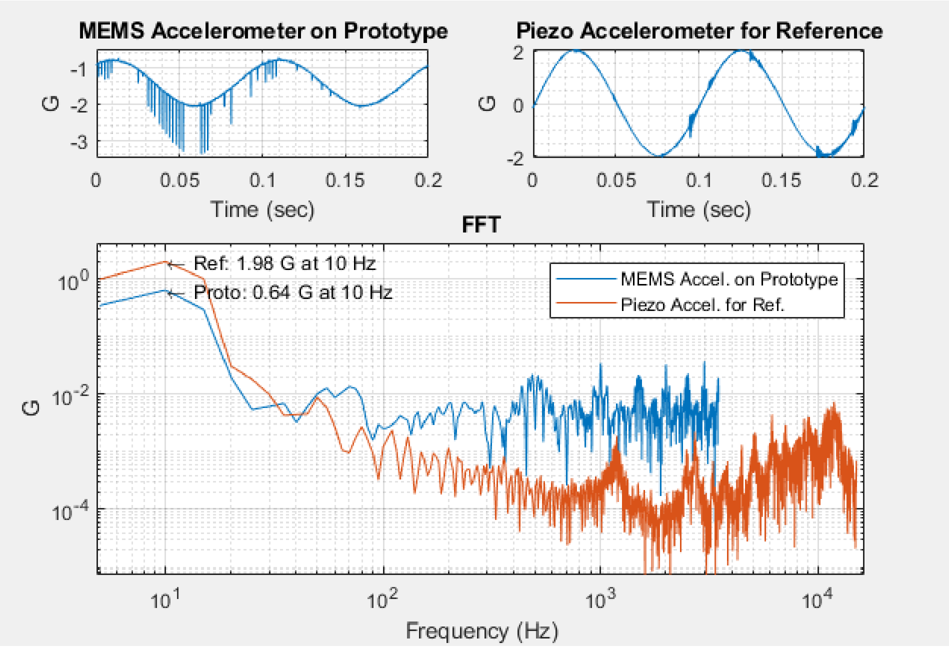

Figure 3. Time series plots and frequency spectrum of the MEMS based prototype compared to a reference piezo accelerometer, both mounted on a shaker table. The sample errors are evident in the time series plot, with the resulting noise in the frequency spectrum.

The prototype samples one axis and then switches to the next axis until 1536 samples were collected for all 3 axes. In the time series the sampling errors manifest as downward spikes, and in the FFT the noise floor is a couple orders of magnitude greater than the reference. The sensor vendor (ADI) recommended including a low-power nearly zero footprint op amp in the design that all but eliminated any potential switching noise by the MUX. The simultaneous sample rate is now only limited by the microcontroller OS.

It was also found that while most of the switching transient amplitude has been eliminated, a small residual capacitance affects the simultaneously-sampled measurement. This can be observed as an increase in roughly 0.04g compared to the single-channel measurement. This is well within acceptable measurement error and was not considered a problem.

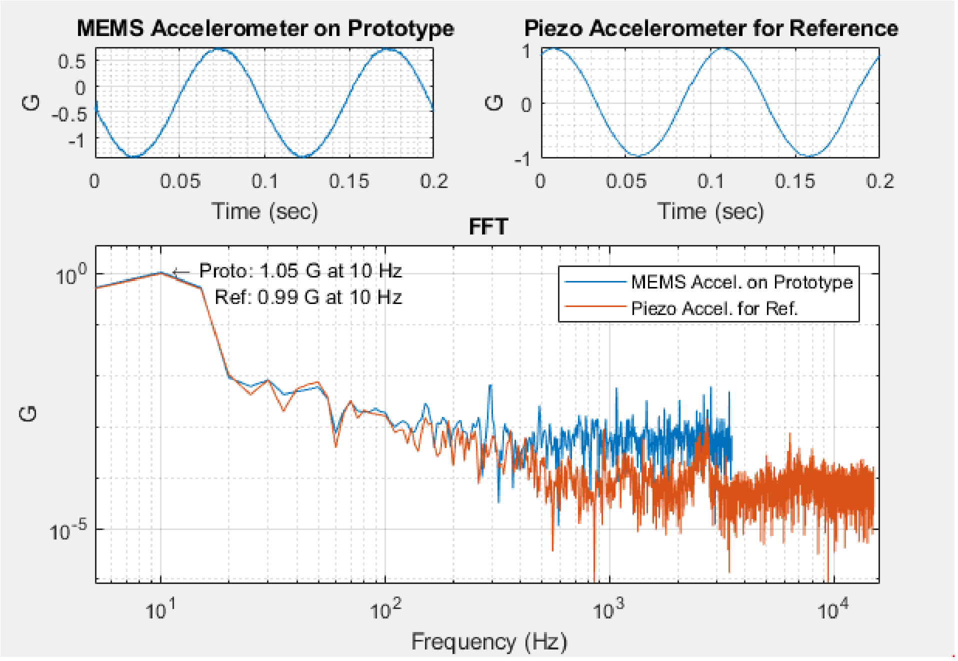

Figure 4. The improved performance is evident once the errors induced in the sampled data are addressed.

5. ENERGY HARVESTING

Both Thermal Energy Generator (TEG) and RF Energy harvesting technologies are under investigation. The power management circuit is designed to accept additional current from any source to charge a 1F, low leakage super capacitor. For this prototype, a TEG generator is added to the design for experimenting with the amount of power that might be generated. Several experiments are performed to test the TEG charging capabilities.

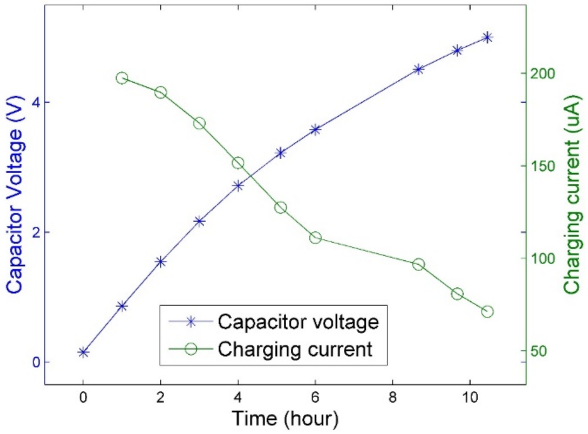

Figure 5. In this case, a temperature differential of 13C is measured across the electrodes of the TEG, presenting 67mV at the input of the charging circuit. The circuit took 10 hours to charge the cap to +5Vdc.

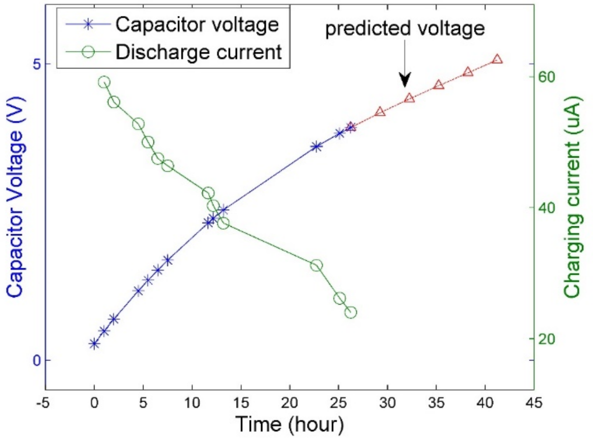

Figure 6. In a second experiment, a temperature differential of 9.6C is measured across the electrodes of the TEG, presenting 40mV at the input of the charging circuit. The circuit took 48 hours to charge the cap to +5Vdc.

Once the capacitor was charged, measurements were taken with no load to estimate the impact of circuit leakage.

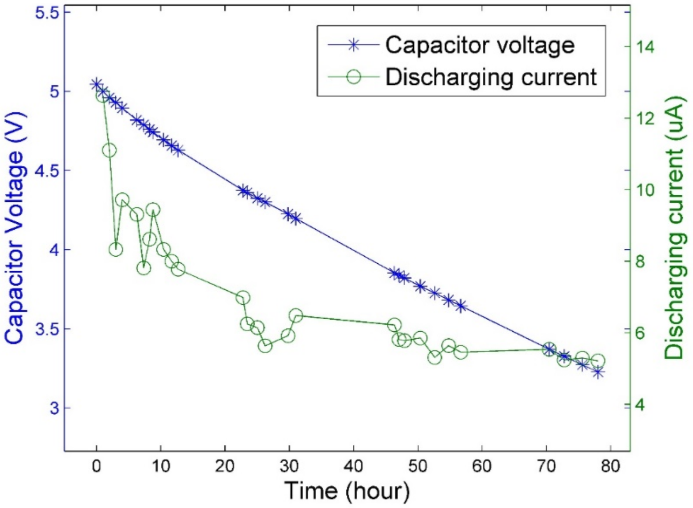

Figure 7. The leakage current for the circuity is about 6 uA. After losing the energy source, the circuit may remain on standby for approximately three days.

During data sampling, the cap discharges 3 mV for wakeup, 512 measurements on all 3 axes, and a write cycle to flash memory (or 0.06% of charge).

Once the initial BLE communications were up and running, it was found to discharge 250 mV for new data and transmit (we believe that this can be reduced in the future). Each data sample and transmission cycle discharges roughly 0.3V from the supercap, demonstrating our expectation that the radio transmission would dominate the power budget. The device continues to function until the power supply drops below 3.3V. In practice, 6-7 transmissions are likely without recharging the TEG energy source.

Improvements in the charging performance of a TEG may be to position the generator such that airflow from a local source will help to reduce the temperature of the sink side, increasing the average temperature differential, hence the power harvested over a given period of time.

6. NEXT STEPS AND FUTURE WORK

The 2nd revision will reduce the size further, and the design team may consider a 2-stack PCB to reduce the footprint at the expense of height. Low hanging fruit might include replacing the external 16-bit ADC with the internal 12-bit ADC of the microcontroller. Some testing with the integrated converter will be required to ensure adequate resolution for the measurements.

Also, a sound partitioning strategy would be to separate the sensor plus DAQ from the Radio, to make it easier for future component replacements based on results achieved. We will also probably continue to keep a separate MCU (plus memory) for flexibility regarding sensor signal processing. This provides flexibility to provision with capable components, and avoids problems and risks of trying to use the radio chip resources, such as filling the memory, counting on vendor support and trying to understand protocol code.

Other sensor features to add include:

Configuring the sensor MCU for selectable data collection intervals, such as taking a data sample every 1, 4, 6, 12, 24 hours.

Investigate just how much flash memory storage is enough. The target sample size is defined as 0.1 seconds with at least 9ksps sample rate (2.56x the max frequency of interest is considered a minimum oversampling rate), with the ability to buffer multiple sets of data (to manage data transmission intervals). The current design uses 4M bit of Flash memory. A decision needs to be made regarding how many datasets to buffer, as too much data requires excessive power to transmit in addition to replicating calculations.

Adding elements of local control to the sensor, such as user initiated device wake up and data capture, which would be useful for research and debugging. This might be implemented with an extremely low-power, low-accuracy MEMS accelerometer to use purely for motion-based event detection wake-up (ie ADXL362). Another option may be to consider a very low power Wake Up Radio (WuR). Other event criteria to be defined.

Regarding the radio and protocol, we will consider transitioning to BLE5.0, for higher speed transmission and smaller size data packets, if necessary. Ideally, this progression could be implemented with minimal impact on recoding the stack. We have also starting working with an IIoT software vendor to develop the sensor firmware further for interface to a COTS gateway, in order to facilitate deployment in the field for testing data transmission and to collect data for further analysis.

7. CONCLUSION

The high value outcome of this project is in the diagnosis and prognosis approaches developed from analysis of the collected data from the field. The wireless sensor network enables us to deploy in friendly plant without risk of disrupting existing networks or process controls. Working in partnership with a data engineering company (Predictronics Inc), the OEM Subject Matter Experts (SME's) have been developing custom condition indicators for several months and the work is on-going. The early results look very promising – there is potential for automated monitoring of emerging faults that are now identified visually by an experienced specialist, with new ways to detect new faults, and the potential to build a prognostic outlook for earlier identification of problems.

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