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# A smart battery free system for wireless condition monitoring using piezoelectric energy harvester

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**Abstract**— A machine failure is often characterized by a sudden increase in the vibration acceleration level. We propose a wireless and battery-free vibration sensor and a method for condition monitoring and predictive maintenance of vibrating objects such as machines and engines. The principal part of our system is a piezoelectric transducer that acts both as a vibration intensity sensor and in addition as an energy source for the sensor circuitry. Our system consists of a battery-free sensor attached to the monitored object that transmits vibration data to a remote Base Station (BS) wirelessly via Bluetooth Low Energy (BLE) beacons. The vibration data is interpreted remotely by the BS via time-domain readout by analyzing the advertising time  $T_{adv}$  of the beacons received by the BS, that can monitor the vibrations and can send a standby signal to the machines in case of emergent faults.

**Keywords**—piezoelectric, predictive maintenance, wireless vibration sensor, energy harvester, battery-free sensors

## I. INTRODUCTION

Vibration during the operation of equipment and automotive motor engines (thermal or electric), is a common phenomenon. However, excessive vibration amplitude often indicate the deteriorating fault condition, which if not monitored, could lead to component failure or damage of the machine.[1] A suitable vibration monitoring technique is therefore required. Recently, battery free and self-powered vibration monitoring systems have received growing interest, as a result of advancements in IoT systems. [2,3] Our work

introduces a battery-free system to implement failure detection based on measuring acceleration and its deviation from nominal values of non-defective parts. Recent developments in micro and nanoelectronics have led to miniaturization of vibration monitoring devices. These devices must operate remotely and wirelessly with power requirements in the order of several microwatts. [4,5] Most of the vibration sensors are located at places that are difficult to reach and their frequent battery replacement would imply a costly maintenance issue. Although microscale ambient energy harvesters may not be able to provide the power for continuous operation of Wireless Sensor Network (WSN), it is sufficient to power these nodes in an intermittent manner. Therefore, the WSN needs to be designed smartly with low power consumption while awake, and negligible power consumption during sleep mode. Typical self-powered WSN nodes used for condition monitoring are powered by a battery, thus needing replacement from time to time. [6] In this work, we present a system that replaces the battery with a capacitor powered by a lead-free Piezoelectric Energy Harvester (PEH) made from Lithium Niobate [7,8] of area  $1\text{cm}^2$  and thickness  $500\ \mu\text{m}$ . The remote sensor and BS implement a BLE communication scheme, which is self-starting and fully autonomous. The BS implements a condition monitoring algorithm, for the remote fault detection. The paper is arranged as follows: Section II describes the system; Section III reveals the setup and the results and section IV describes the major conclusions of this work.

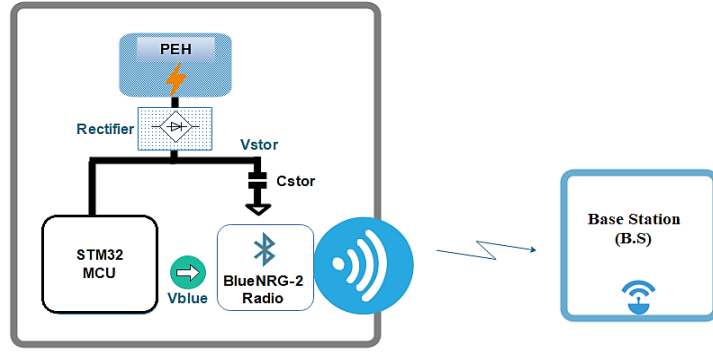


Figure 1: schematic of the vibration sensor

## II. SYSTEM DESCRIPTION

As illustrated in Fig 1, the vibration sensor consists of a PEH for power supply, and rectification system (full bridge), a capacitor (220 $\mu$ F) for energy storage, STM32L0 microcontroller for voltage monitoring, and a BlueNRG-2 BLE radio. [4] The size, geometry, and mechanical stress of the PEH have been optimized using Finite Element Simulations. [7] The sensor node can be connected wirelessly to a BS that performs data processing and continuous data transfer to the cloud. BLE is used as the communication standard because of its low power consumption and the compatibility and ease of BLE use in portable devices to communicate with the WSNs. The sensor node is designed to transmit beacons intermittently, and thus the radio is shut down after every transmission to minimize the overall energy consumption. The total power consumed by wireless sensor device  $P_{WSN}$  in each cycle can be characterized by the power consumed by its components and their processes and expressed as:

$$P_{WSN} = P_{SB} + P_{MCU} + P_S + P_{TX} \quad (1)$$

where  $P_{SB}$  is the standby power consumption,  $P_{MCU}$  is the power consumed by the processor unit,  $P_S$  (0 in our case) is the power consumed by the sensor, and  $P_{TX}$  is the power consumed by the BLE transmission section respectively. The peculiarity and advantage of this system are that the PEH plays the dual-role of energy harvester that supplies the power to the whole system and also acts as a vibrational sensor. The monitoring of the input vibration is realized by measuring the time between successive beacons, also known as advertising time ( $t_{adv} = t_C - t_A$ ), emitted by the wireless sensor radio to the BS as shown in Figure 2.

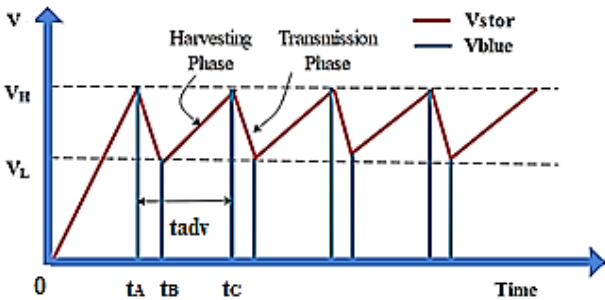


Figure 2: Typical time evolution of  $V_{stor}$  and  $V_{blue}$ , showing the harvesting and transmission phases

When the capacitor voltage  $V_{stor}$  reaches the highest value  $V_H$ , the system turns to the transmission phase, where the microcontroller supplies the BLE through one of its General-Purpose Input/Output (GPIO) pins. Soon after the transmission phase ( $t_B - t_A$ ), when the voltage drops to the lowest values, the microcontroller shuts down the BLE radio, turns in sleep mode, and the whole system returns to the energy harvesting phase ( $t_C - t_B$ ). The sensor works on the principle that the time delay between two successive beacons depends on the input acceleration of the PEH. The values of  $V_L$  and  $V_H$  are chosen such that the voltage never exceeds the rated maximum (3.6V) and a minimum supply voltage (1.6V) of the STM32L0 microcontroller. During the harvesting phase, the harvested power  $P_{harvested}$  varies quadratically with the power of two of the acceleration  $a_{cc}$ :

$$P_{harvested} = K_{acc} \cdot a_{cc}^2 \quad (2)$$

The harvested energy  $E_{harvested}$  in the capacitor during the energy harvesting phase is a constant that depends on the capacitor value  $C_{stor}$  and the fixed voltage value  $V_L$  and  $V_H$ . The time interval between two successive beacons is called the advertising time  $t_{adv}$ .  $E_{harvested}$  is related to  $P_{harvested}$  and the time that it takes to charge that is nearly the same as the advertising time, between two beacons, since  $(t_C - t_B) \gg (t_B - t_A)$ .

$$P_{harvested} \approx \frac{E_{harvested}}{t_{adv}} \quad (3)$$

Due to this approximation,  $P_{harvested}$  is slightly overestimated. The communication between the sensor and the base station is made through Bluetooth wireless beacons. From (2) and (3), it is possible to estimate acceleration  $a_{cc}$  in terms of  $t_{adv}$  as:

$$a_{cc} \approx \frac{S_v}{\sqrt{t_{adv}}} \quad (4)$$

where, the constant  $S_v$  is the calibration constant and is determined from inverse of slope of the calibration curve, as described in Figure 3d. Equation (4) can be implemented in the embedded firmware of the BS so that the acceleration  $a_{cc\_BS}$  can be remotely and indirectly measured at the BS that can measure  $t_{adv}$  from the received beacons.

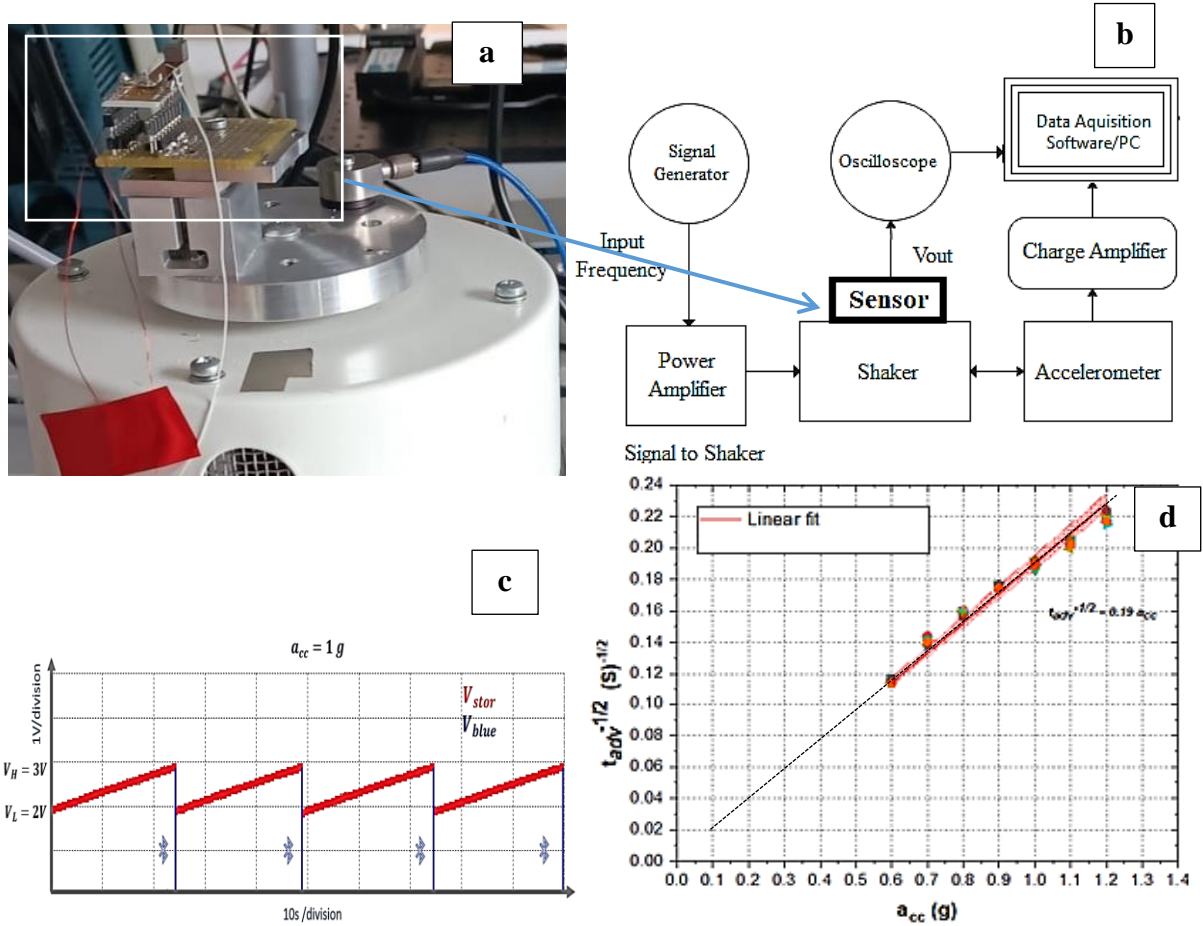


Figure 3: (a) shaker setup with the PEH for measurement (b) experimental setup schematic (c) experimental measurement of advertising time for  $a_{cc} = 1g$  (d) Calibration curve displaying the advertising time  $t_{adv}$  vs input acceleration  $a_{cc}$  with linear fit of the experimental measurement data with  $1/Sv = 0.19 \text{ m}^{-1} \cdot \text{s}^{1.5}$

### III. RESULTS AND DISCUSSION

As shown in Figure 3c, the voltage  $V_{stor}$  across  $C_{stor}$  toggles between set values of  $V_L = 2V$  and  $V_H = 3V$ . The advertising time  $t_{adv}$  can be determined from the intervals between two Bluetooth beacons as identified from  $V_{blue}$ . The  $t_{adv}$  at  $1g$  acceleration is determined to be  $\sim 25s$  at  $1g$  input acceleration as in Figure 3c. The sensor characterization in terms of Limit of Detection (LoD) and sensitivity in response to the vibrational acceleration has been carried out at room temperature in the air ambient as shown in Figure 3 (a, b). The vibration sensor, positioned on the shaker as in figure 3a, has been subjected to various vibration levels with the acceleration  $a_{cc, in}$  varying in the range  $[0.6 \text{ g} - 1.2 \text{ g}]$ . Figure 3b reveals how the time  $t_{adv}$  decreases with the increase of the acceleration  $a_{cc}$  in agreement with equation 4.

The test measurements unveil that it is possible to measure remotely and wirelessly at the BS.  $Sv$ , the calibration constant is determined to be  $5.25 \text{ m} \cdot \text{s}^{-1.5}$  from inverse of the slope of the calibration curve (Figure 3d). The measurement results within the range of acceleration  $[0.6-1.2 \text{ g}]$  are repeatable with an error consistently below 11%, measured over different tests. The BS can therefore receive beacons from wireless vibration sensor node, placed on the vibrating parts of machines under

test, and exercise predictive maintenance or fault detection by simply measuring the advertising time  $t_{adv}$  of the received beacons as shown in Figure 4a,b. For long-term predictive diagnosis of machines, the wireless vibration sensor node can be embedded in specific mechanical parts that require regular maintenance as bearings, gears, conveyors, turbines, shafts, valves, and the like. When a mechanical fault happens, there is a sudden increase in the rate of change in the detected acceleration amplitude at the BS. The instantaneous rate ( $K_t$ ) can be monitored by the BS, by measuring the vibration accelerations at two successive time intervals as:

$$\text{Rate } (K_t) = \frac{a_{cc}(t_2) - a_{cc}(t_1)}{(t_2 - t_1)} \quad (5)$$

where,  $a_{cc}(t_2)$  and  $a_{cc}(t_1)$  are the amplitudes of accelerations at time intervals  $t_2$  and  $t_1$ . The base station calculates the instantaneous rate  $K_t$ , and can send interrupt or standby signals to the machine control. Also, alarm signals can be initiated to the user if the rate is above a critical threshold  $K_c$  of machine failure, as shown in Figure 4.

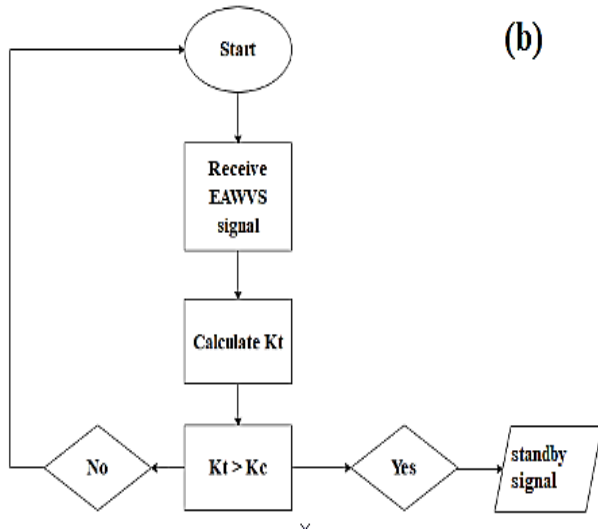
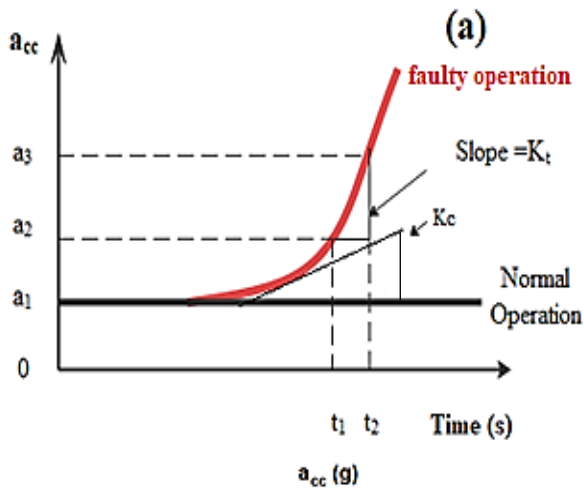


Figure 4: (a) Example of an increase in acceleration between time  $t_1$  and  $t_2$  (b) Application scenario algorithm of the predictive maintenance with wireless vibration sensor

In addition, less complicated algorithms such as limiting the machine operation to a critical acceleration threshold to prevent the machine failure, can be implemented. The LoD of the system, is only determined by the standby power consumption of the system ( $<5\mu W$ ), and can further be improved by improving the design of the harvester, and thereby improving the energy density per unit area.

#### IV. CONCLUSIONS

In this work we proposed a novel battery free system for condition monitoring of and predictive maintenance of vibrating objects such as machines and engines. The proposed system composed of lead-free piezoelectric energy harvester, voltage monitoring circuit and BLE radio could detect the input vibration as low as 0.6 g. Experimental tests have shown that the wireless vibration sensor and BS system can deliver repeatable and accurate sensing functionality with less than 11% maximum error, consistently over different tests. The BS upon receiving beacons from one or more

wireless vibration sensor nodes, placed on the vibrating parts of machines under test, exercise predictive maintenance or fault detection by simply measuring the advertising time  $t_{adv}$  of the received beacons. This feature therefore involves less complicated electronics at the sensor side, than analog architectures and therefore lower energy consumption, compared to similar condition monitoring sensors [10], which is key for energy-autonomous systems. Therefore, using the proposed algorithm, the BS, can send interrupt or standby signals to the machine control upon by estimating the rate  $K_t$ . Also, alarm signals can be initiated to the user if the rate is above a critical threshold  $K_c$  of machine failure. The sensor is light compact, occupying an area of 2cm X 2cm. Thus, the proposed novel sensor system for condition monitoring provides a maintenance-free, install and-forget approach, thanks to the unnecessary for an external power source, making it ideal for use in industrial application.

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