Powering Wireless Sensor Nodes for Industrial IoT Applications using Vibration Energy Harvesting

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Abstract—Electromagnetic Vibration Energy Harvesting (EM-VEH) is an attractive alternative to batteries as power source for wireless sensor nodes within the Internet of Things (IoT) in industrial environments. Indeed, there is often an abundance of available kinetic energy, in the form of machinery vibrations, that can be converted into electrical power through energy harvesting techniques. Ambient vibrations are generally broadband and multi-modal configurations can be exploited to improve the mechanical-to-electrical energy conversion. However, the additional challenge of energy conditioning (AC-to-DC conversion) brings into question what specific type of performance is to be expected in a real industrial application. This paper reports the operation of two practical IoT sensor nodes, continuously powered by the vibrations of a standard industrial compressor, using a multi-modal EM-VEH device, integrated with customised power management. The results show that the device and the power management circuit provides enough energy to receive and transmit data at minimum intervals of less than one minute. Descriptions of the system, test-bench, and the measured outcomes are presented.

Index Terms—electromagnetic vibration-based energy harvesting, power management, internet of things, preventive maintenance

I. INTRODUCTION

The IoT proposes an environment where individual nodes such as industrial machinery, home appliances, and wearable technology are all interconnected for data collection and exchange, in particular using Wireless Sensor Networks (WSNs) (Fig.1). The current worldwide investment in IoT of around USD 130 billion [1], with up to 7 billion nodes currently connected [2], has created a thriving market that is forecasted to grow to USD 1.567 billion by 2025, with 21.5 billion of connected nodes [2]. The IoT market consists of an increasing number of start-up companies, which are defining different stages in the technology development, such as: Sensors, Connection (sensor networks), Storage (solid state), Processing (big-data management), Telecommunications, and Learning (Artificial Intelligence -AI-). It has been suggested that the purpose of this evolution is bringing computer systems to a state of Awareness. As such, health care, finances, and manufacturing are expected to be re-shaped to include features for Augmented Reality (AR), of which IoT is a foundation.

An underlying need for resilient interconnection of sensor nodes (SNs) in the IoT is a reliable power supply, and the current standard is the use of batteries. However, expected industrial applications of the IoT such as preventive maintenance require pervasive sensing, with challenges such as a large number of SNs to power, and in places that might be difficult to reach. In such cases, the cost of battery replacement represents a significant barrier to the widespread use of WSNs [3]. An alternative to batteries is represented by renewable power sources and, in particular, energy harvesting [4] – the collection of small amounts of power (less than 1 W) taken from environmental sources, to feed low-power-consumption loads. Indeed, it is estimated that the operational cost over the product life-time of a harvester-assisted application is reduced to one third of that of a battery-powered one [5]. One of the most popular options is Electromagnetic-Vibration Energy Harvesting (EM-VEH), which exploits the relative motion between a coil and a magnet produced by mechanical vibrations, that induces AC voltage in the coil. Traditionally these systems have a narrow frequency bandwidth and must be tuned to the dominant frequency of the ambient vibrations [6].

To overcome the problem of narrow bandwidth, a two-degree-of-freedom (2DoF) EM-VEH that exploits multiple masses and a patented velocity-amplification principle has been developed by the authors’ group [7]–[10]. In this harvester, harmonic and random excitations can be used as vibration sources for producing higher voltage and power than in prior art. To make this particular technology usable, optimised power conversion (AC to DC) and management is needed. Ultimately, it is of more interest for IoT applications to understand the capabilities of the overall EH system when used with ambient vibration sources, such as those found in
industry, to power real WSN loads. These topics have not yet been explored for the particular harvester under discussion.

This paper addresses these needs by first introducing a power management technique specific for the multi-modal EM-VEH device reported in [9]. Then, the performance of the overall EH system is explored using input vibrations commonly found in industry to continuously power IoT sensor nodes of two different communication technologies: LoRaWAN and Bluetooth. In the next sections, descriptions of the harvester, power management system, testbed, experiments and results will be presented.

II. ENERGY HARVESTING FROM AMBIENT VIBRATIONS

Common vibrational energy harvesters are based on linear mass-spring systems with a narrow frequency response, which requires that they need to be tuned to the main frequency of the external excitation. This usually limits the energy transfer in realistic applications, since ambient vibrations generally have a broad spectrum with several peaks [6]. An alternative to overcome the problem of narrow bandwidth is the two degree-of-freedom (2DoF) velocity-amplified EM-VEH introduced in [9]–[11].

The harvester is currently going through a commercialisation path, and it has been branded by Stokes Power [12], with the commercial name of VEH-1. Fig. 2a shows its overall size with reference to a D-battery: diameter 40 mm, height 74 mm.

![Fig. 2. Stokes Power’s VEH-1: (a) illustration of the scale of the harvester with reference to a D-battery; (b) Schematics of the harvester.](image)

The device is based on a concept developed by the authors in [9] and its schematics is shown in Fig. 2b: it comprises two masses oscillating vertically, one inside the other, between four sets of springs. Impacts between the masses can occur allowing momentum transfer from the heavier mass (the outer mass) to the lighter (the inner mass), leading to velocity-amplification. Electromagnetic transduction is chosen as the conversion mechanism since it is easily implemented in a device that exploits velocity-amplification: the outer mass acts as a housing for the coil and the magnet: improving the velocity of the inner mass increases the output voltage and the output power ($P_e \sim v^2$).

III. INDUSTRIAL TEST BENCH

The VEH-1 presented in Section II was tested on an electrodynamic shaker reproducing the vibrations available on an industrial air compressor and it was shown that the device could generate enough energy to power two wireless sensor nodes. In the next subsections the experimental setup and the two different nodes are presented.

A. Input Mechanical Vibrations

Typical sources of mechanical vibrations in industry are devices linked to motors. While industries like mining and concrete-block manufacturing have machinery with stronger vibrations, the most commonly found equipment are pumps, fans and compressors. In this study, the acceleration pattern of the vibrations on a medium-range-power air compressor was measured in-situ, in a real industrial environment; and it is shown in Fig. 3a. The RMS of the acceleration is $a_{rms} = 0.73g$ ($g = 9.81 \text{ m/s}^2$) and the main frequency is 13 Hz as visible from the Power Spectral Density (PSD) shown in Fig. 3b.

![Fig. 3. Vibrations measured on an industrial air compressor: (a) time series; (b) power spectral density.](image)

The measured acceleration pattern was then used to emulate these mechanical vibrations in the laboratory, using the experimental setup shown in Fig. 4. The harvester was fixed to an LDS V406 electrodynamic shaker and a PCB Piezotronic accelerometer, mounted on the head of the shaker below the harvester, was used to provide a feedback control to set the acceleration to the desired amplitude level. The output voltage was measured across a variable resistor whose value was fixed to match the optimal load $R_L$. Labview was used to drive the shaker and to acquire signals from both the accelerometer and the harvester.

The open circuit voltage generated by the harvester is shown in Fig. 5a and it has RMS / peak voltage levels of 8.4 V / 17 V. Figure 5b additionally reports the voltage measured across a load resistance $R_L = 12050 \text{ } \Omega$ which has approximate RMS / peak voltage levels of 3.45 V / 8.6 V. The harvested power, calculated using $P = V_{rms}^2 / R_L$, is 0.98 mW. In this study, this level refers to the absolute maximum power that the harvester is able to deliver potentially, before any power conditioning.
B. Output Low-Power Loads

Sensor nodes of two of the most representative communication technologies for IoT applications have been chosen as the low-power loads in this study: LoRaWAN and Bluetooth [13].

a) LoRaWAN End-Device Node: The first load is a LoRaWAN end-device developed by Pervasive Nation, an Irish IoT testbed operated by the CONNECT Research Centre, for use in its national network through a custom gateway. This small form-factor interface board reports data of a selection of on-board general purpose sensors (accelerometer, Hall sensor, temperature and humidity) over LoRaWAN [14].

The LoRa board feeds off a 3.3 V (nominal) DC voltage, in the range 2.5 V to 3.6 V, which is originally provided by a coin-type battery. The operation mode within the protocol was modified so that the board implemented minimum power consumption with a single sensor (magnetometer). The practical current consumption profile of the board, for one round of data Reception/Transmission (Rx/Tx), was measured; and it is depicted in Fig. 6.

The device goes through this cycle and goes back to its sleep mode, where current consumption decreases to a few micro-Amps (negligible). Table I identifies the average power consumed by the board for different sleep times (at a nominal input voltage of 3.3 VDC). Usual Tx/Rx rates in LoRaWAN applications admit sleep times of up to 15 minutes [15].

b) Bluetooth Sensor Node: The second load is the Texas Instruments (TI) CC2650 SensorTag. This is a more standard IoT device that supports 10 low-power sensors, embeds expansions for customised IoT applications, and it typically feeds off a coin-type battery with a 3 V (nominal) DC voltage, in the range 2 to 3.4 VDC. The board is able to connect with a mobile app via Bluetooth, where the transmission rate and number of sensors enabled in the session can be modified [16].

Using the board features, an application with three simultaneous enabled sensors (ambient light, and local and ambient temperatures) was configured. The current consumption profile, for one round of data Rx/Tx is presented in Fig. 7 (for a nominal 3 VDC input voltage), and the power consumption for different sleep times is presented in Table II.

IV. POWER MANAGEMENT FOR EM-VEH

The SNs that are powered by the proposed EM-VEH technique have embedded electronics designed to be powered from a coin-type battery of ~ 3.3 VDC. Since the output voltage of the VEH-1 is of AC nature, the power management (PM) strategy must first implement AC-to-DC electrical energy conversion, and then further DC voltage regulation to deliver a reliable DC supply near 3 VDC, while maximising the energy transfer. A schematic of the PM strategy used in this study is introduced in Fig. 8. The basic features are detailed next.
The first stage in the PM is front-end AC-to-DC energy conversion. Several PM methods have been proposed in the literature on EM-VEH; from which the synchronous active rectifier is one of the most efficient strategies, while also providing further regulation [17]. However, this technology has not matured enough yet to be found in commercial PMICs. Another form of active rectification is the Negative Voltage Converter (NVC) – a bridge rectifier implemented with MOSFETs (and an active diode) that reduces the device voltage drop, when compared against using diodes [18].

These solutions are based on the idea that EM-VEH produces AC voltages of peak values less than 1 V [6], which is true for traditional harvesters of this type. However, the VEH-1 is able to deliver higher voltages (open circuit peak voltage $V_{\text{peak}} = 17$ V, Fig 5a) in this particular application. Experimental work confirmed that the use of a NVC presented no particular advantage when compared to a (Schottky) Diode Bridge Rectifier, which was finally chosen as seen in Fig. 8. The rectified version of the harvester voltage $v_h$ (shown in Fig. 5a), measured across a filter capacitor, is $v_{in}$ and it has an average value of 15 VDC. This average open-circuit value is less than $V_{\text{peak}} = 17$ V (Fig. 5a) because the input signal is not perfectly sinusoidal. Also, the value of $v_{in}$ is further reduced due to the forward voltage drop caused by the rectifiers (of $<240$ mV per diode due to the very-low input current).

The second stage in the PM implements DC-to-DC voltage regulation. Again, due to the very-low voltage outputs of traditional EM-VEH devices, the most common topology for DC-to-DC conversion in several commercial PMICs is a boost converter [19], usually rated for 5 V, which is not adequate for the voltage range of the VEH-1 ($\sim 17$ V in Section III-A).

The control technique for the switching in the converter is specific for EH. This is because a SN can operate continuously only if the energy production is equal or superior to the consumption, which is challenging for any EH supply so that low-power-management strategies are required. On the load side, this is achieved by implementing customised scheduling with data Tx/Rx implemented only every several seconds/minutes (Section III-B) [20]. On the supply side, Maximum Power Point Tracking (MPPT) techniques assist the power delivery, which are commercially implemented by a Power Management Integrated Circuit (PMIC).

Theoretically, MPPT involves matching the impedance of the load observed by the harvester to that of the harvester. Commercially this is typically achieved by well-known algorithms such as perturb-and-observe, which adjusts the input voltage until the measured input power is maximised; this was originally proposed for photo-voltaic (PV) cells [21].

Due to the high number of turns in the coils of the VEH-1 design, the coil resistance ($R_s$) and coil inductance ($L_s$) in the typical dynamic electrical model of an EM-VEH harvester (shown in Fig. 8) are high; in this study, they were measured to be $3840$ $\Omega$ / $282$ mH. This is larger than the usual few ohms/milli-henries in typical EM-VEH designs [22], which makes the implementation of the MPPT vital and particularly difficult, since the high input impedance yields a more unstable input DC voltage. With the premises above, and after a thorough commercial survey, the ST Microelectronics’ SPV1050 [23] was chosen as the most adequate PMIC for the application. It implement DC-to-DC buck-boost conversion mode (allowing input voltages up to 20 VDC), and MPPT from the harvesting source that stores the energy in a super-capacitor $C_{\text{storage}}$, and delivers regulated 3.7 VDC to the low-power load, as outlined in Fig.8. The output voltage was chosen as the maximum admissible in the range of the loads (Section III-B). As soon as the harvester source is connected, the PM system goes through the following intervals:

### A. Cold-Start Interval

The (rectified) input from the harvester $v_{in}$ is directly connected to the storage device $C_{\text{store}}$ so that $v_{in} = v_{bus}$ during the cold-start interval $\Delta t_{cs}$, which runs for: $150$ mV$< v_{bus} < 2.6$ V. Fig. 9 shows the bus voltage on the storage super-capacitor during cold-start. It took around 22 minutes for $C_{\text{storage}}$ to charge to 2.6 V under the excitation detailed in Fig. 3.

![Fig. 9. Bus voltage during cold-start.](image)

### B. Switching Interval

During the switching interval $\Delta t_{\text{sw}}$ after the bus voltage has reached 2.6 V, the internal buck-boost DC-to-DC converter of the PMIC operates according to the MPPT algorithm: the converter will stop switching for 400 ms, every 16 s, time during which $v_{in}$ is allowed to reach its open-circuit voltage $V_{oc} = 15$ V (maximum harvester voltage), in order to record this level. Once this interval is elapsed, the converter operates again, setting its own impedance such that $v_{in}$ stays as close as possible to the (previously) programmed maximum power point voltage $V_{MPP}$, which is a percentage ($MPP_{\text{ratio}}$) of $V_{oc}$, such that:

$$V_{MPP} = MPP_{\text{ratio}} \times V_{oc} \quad (1)$$

The ideal $MPP_{\text{ratio}}$ for EH using PV panels and Thermoelectric Generators (TEGs) is well identified in the literature as 50% and 80% of $V_{oc}$, respectively. For EM-VEH, however, no analytical description is available. In this study, a theoretical study has determined this ratio to be above 39%, and it was ultimately identified experimentally. Fig. 10 shows the bus voltage during the switching interval, for different MPP ratios. The results show the optimal MPP ratio is around 60%, so this is the value to be programmed in the PMIC.
C. Operational Interval

Once $v_{bus}$ across the storage device rises above 3.7 VDC (end-of-range levels of the loads defined in Section III-B), an internal output switch of the PMIC closes, making $v_{bus} = v_o$, so the energy in $C_{storage}$ is finally transferred to the load, and thus starting the operational interval $\Delta t_{op}$.

During this interval, the DC-to-DC converter is enabled/disabled intermittently such that $v_{bus} = v_o$ remains close to 3.7 VDC based on internally-defined hysteresis levels. Furthermore, an undervoltage protection opens the output switch when $v_{bus} = v_o$ falls below a lower threshold level of 2 V, hence returning to either cold-start or switching modes, depending on the voltage drop. The value of $C_{storage} = 0.1 \text{ F}$ was designed considering this behaviour.

The response of this interval is unique for each one of the loads described in Section III-B, and the results are reported in the next section.

V. EXPERIMENTAL RESULTS

The power management solution proposed for the VEH-1 in the previous section was implemented in a $60 \times 30 \text{ mm}^2$ PCB, enclosed in a $29 \times 74 \times 49 \text{ mm}^3$ box with two I/O BNC connectors, as seen in Fig. 11. In the following subsections, the distance between the node and the receiver was 2 meters.

A. LoRaWAN Node

During the operational interval, the LoRa board transmits the data of its magnetometer sensor to a gateway which makes the data available over the internet through the LoRaWAN protocol. Different data rates (sleep times) were tested on the board to find the minimum for which the board was kept energised. The screen shot of the data in Fig. 12 shows how after changing from a sleep time of 20 seconds to 30 seconds, the embedded “battery charge” measurement switches from a dropping charge (100% to 92%) to a stable 100% charge. Hence, 30 seconds is the minimum data rate achievable in this application. Note that this is more frequent than the usual 15 minutes data rate in the protocol.

B. Bluetooth Node

The Bluetooth SN transmits the data of three sensors to an iPhone7 with iOS 12.0.1 using its SensorTag app. Screen shots of the results over time are shown in Fig. 13. With a data rate of two seconds, and in spite of a high initial peak of current consumption that sets the voltage lower than the “100% battery charge” measured by the SN, it finally settles in about 76% charge, and maintains this level over time.

C. Efficiency

The performance of the energy transfer is expressed in terms of the relative efficiency $\eta$, defined as the ratio of output and input powers $\eta = P_o/P_{in}$. $P_{in}$ is the maximum raw power that the harvester is able to deliver; 0.98 mW (Section III-A). $P_o$ was estimated in each functional stage of the PMIC. During the cold-start and switching intervals, $P_o$ is the power injected in $C_{storage}$, and it was obtained by measuring the voltage across it and numerically estimating its through-current $i_C$ using the basic model of a super-capacitor (in series its Equivalent Series Resistance – ESR), by numerically solving the differential equation:

$$396$$
v_{bus} = ESR \times i_C + \left( \frac{1}{C_{storage}} \right) \int_0^t i_C dt \tag{2}

This estimation is necessary due to the challenge of measuring extremely low currents, something non-viable in this study. \( P_o \) can then be estimated over the measurement interval of \( v_{bus}, [t_o, t_f] \) as:

\[
P_o = \frac{1}{t_f - t_o} \int_{t_o}^{t_f} i_C v_{bus} dt \tag{3}
\]

During cold-start, the efficiency was found to be \( \eta = 236.17 \mu W / 980 \mu W = 0.24 \). During switching, it was \( \eta = 378.36 \mu W \) / \( 980 \mu W = 0.39 \). For the Operational interval, the minimum operational duty cycle indicates the power that the load is absorbing, and is inferred from the current profiles/tables in Section III-B. For the minimum duty cycles of 30 seconds / 2 seconds for the LoRa/Bluetooth boards, the efficiency is estimated over the measurement interval of \( v_{bus}, [t_o, t_f] \) as:

\[
P_o = \frac{1}{t_f - t_o} \int_{t_o}^{t_f} i_C v_{bus} dt \tag{4}
\]

This in agreement with other energy conversion techniques for EH [24]. The results in this section validate the operation of the proposed EH system.

VI. CONCLUSION

This paper reported the successful operation of two IoT sensor nodes, which are continuously powered by real industrial vibrations from a typical air compressor. The system makes use of a multi-modal EM-VEH device. An customised power conditioning system for this harvest was also proposed. The system is able to power a LoRaWAN sensor node with a duty cycle of 30 seconds, which is more frequent than the 15 minutes usually expected in the protocol. Likewise, a Bluetooth node was energised with a minimum duty cycle of two seconds. The efficiency of the energy transfer is about 30%, which is usual in EH. These results demonstrate the capabilities of this type of EM-VEH in an industrial IoT environment.

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REFERENCES


Pervasive+Nation+LoRa+Board+Setup


