Application Note
Energy Harvesting Solution for Smart Footwear

Abstract

This document presents a feasibility study on using piezoelectric energy harvesting to increase the battery lifetime of smart footwear. The main objective is to use off-the-shelf miniature piezoelectric diaphragm energy harvesters combined with Nowi's NH2D0245 Power Management Integrated Circuit (PMIC) to harvest energy from pressure generated on the insole of a shoe by a human walking, and running motion. This document will present Nowi's own smart footwear prototype using piezoelectric energy harvesting.

1. Summary

There is kinetic energy present in the walking and running movement of humans. This kinetic energy translates into pressure applied to the sole or insole of footwear. Smart footwear is becoming a popular topic in a variety of applications. More and more companies are developing smart footwear products, and Nowi developed its own smart footwear prototype as a feasibility for piezoelectric energy harvesting.

We can summarize the main points of this application as follows:

- The battery lifetime of embedded smart footwear can be increased significantly when utilizing piezoelectric energy harvesting.
- The power consumption and battery lifetime is determined by the amount of samples the system takes from the sensors per second. This sample rate can be set, and optimized depending on what algorithms the smart footwear will provide.

2. Applications

There is a variety of applications, in which smart footwear can be used and (partly) powered by piezoelectric energy harvesting. One of the main applications being smart sports footwear. By implementing embedded electronics and sensors in sports footwear, different metrics on the workout can be measured and calculated. Examples of these metrics are: steps, distance, speed, burned calories etc. Besides workout metrics, smart footwear can also be applied in applications that do not necessarily require a sensor, such as indoor tracking of for instance, medical personnel in hospitals. Another application could be a military application, or at a construction site application, where energy is harvested from walking or running, and powering smart sensing systems in the footwear.

3. Nowi Smart Footwear Architecture

This section presents the system and architecture of the Nowi Smart Footwear prototype.

Figure 1 gives an architectural overview of the Nowi Smart Footwear prototype. When the system is turned on a Bluetooth Low Energy (BLE) module based on Nordic Semiconductors nRF52832 will be searching for a connectable device, which in most cases will be a smartphone. Once a connection with a smartphone is established, the module will sample accelerometer data and store this data on the onboard flash memory chip. Upon request via the BLE connection, this data can be received on the connected device, and the connected device can use this data to calculate metrics based on the workout, such as: running speed, traveled distance, and number of steps.

Figure 2 and Figure 3 show the top and bottom layer of the prototype Printed Circuit Board (PCB) developed by Nowi.

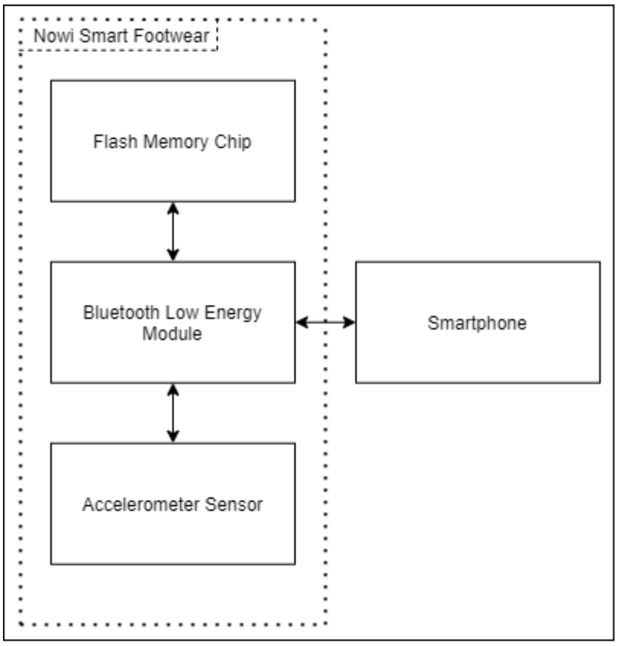

Figure 1: *High level overview.*

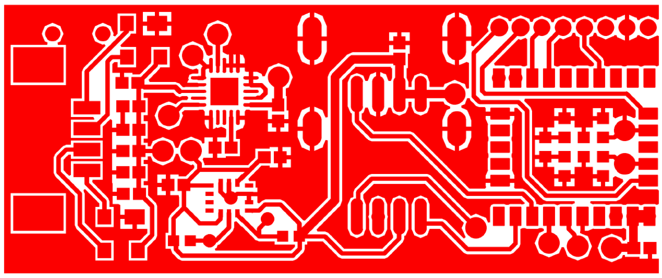

Figure 2: *PCB Top Layer.*

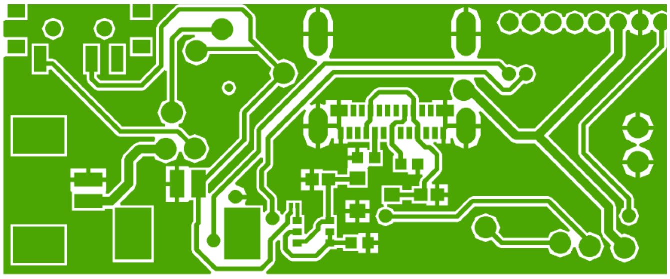

Figure 3: *PCB Bottom Layer.*

4. Power Management

This section presents the power management system of the Nowi Smart Footwear prototype. The power management consists of two parts. Harvesting the kinetic energy of walking and running using Nowi's NH2D0245 PMIC, compensating the power consumption of the Nowi Smart Footwear system. Manually charging the battery using the onboard USB-C connector with constant voltage and a safe constant battery.

4.1. Piezoelectric Energy Harvesting

During a walking or running motion pressure of the human body is applied to the insole of the shoe. The pressure distribution depends mainly on how the movement is executed, and what the body weight is. An example of pressure distribution is given in Figure 4. Piezoelectric diaphragm harvesters, like the one in Figure 6, generate an amount of charge when pressure is applied to them. By implementing multiple of these diaphragm harvesters under the insole, as shown in Figure 5, it is possible to harvest energy from walking and running.

For this prototype it is chosen to go with off-the-shelf piezoelectric energy harvesters. When making custom harvesters the generated energy can increase significantly. The harvester for this prototype has a diameter of 35 mm, the amount of harvesters applied under the insole depends on the shoe size. For this prototype we have configured six of them under the insole.

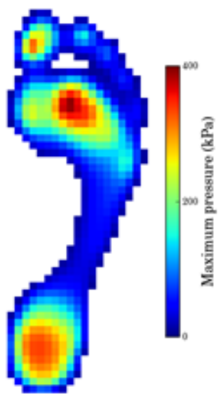

Figure 4: *Pressure distribution example.*

Figure 5: *Configuration harvester.*

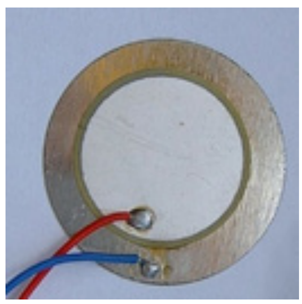

Figure 6: *Diaphragm harvester.*

Figure 7 shows the power management circuitry of the NH2D0245 for piezoelectric energy harvesting. P_1, P_2, and P_3 correspond to the upper three piezoelectric diaphragm harvesters shown in Figure 5, and, P_4, P_5, and P_6 correspond to the lower three piezoelectric diaphragms. In one portion of the walking or running movement, the maximum pressure is focussed on the upper area of the pressure distribution shown in Figure 4, and in the second portion of the movement, the maximum pressure is focussed in the lower area of the pressure distribution. These groups of piezoelectric diaphragms are therefore out of phase and need to be rectified per group.

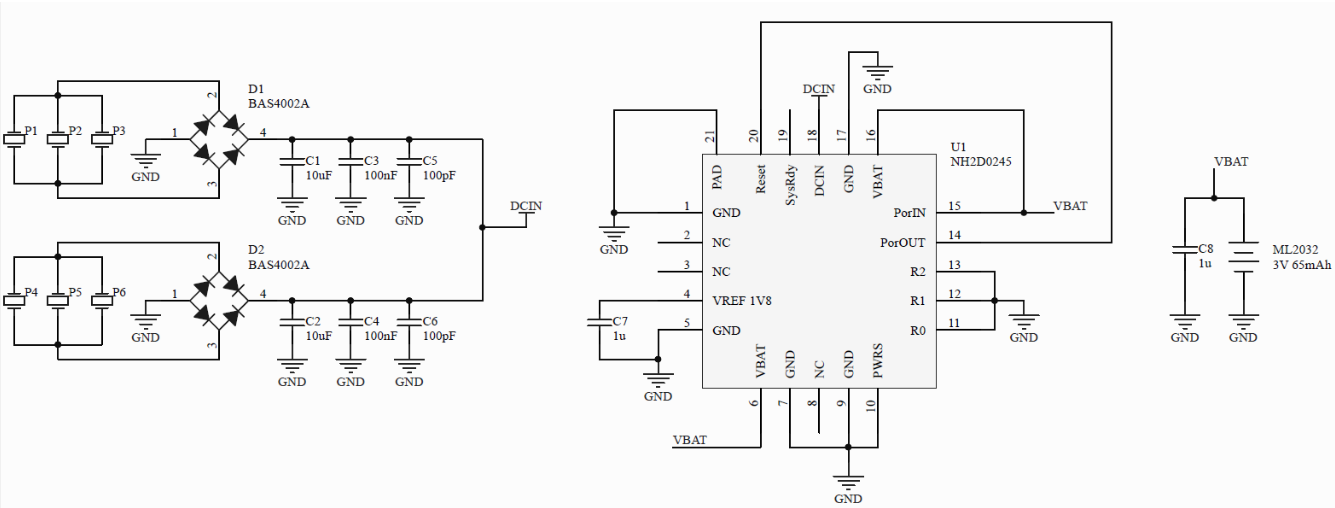

Figure 7: *Power management circuit.*

This rectified and smoothed voltage from the piezoelectric diaphragm harvesters is then fed into the NH2D0245 PMIC, and used to charge a 3 V 65 mAh Lithium-Manganese battery.

The optimal values of the smoothing capacitors can be changed at any time.

5. Energy Harvesting Rate

This section presents the power delivery and battery charging rate of the power management circuitry presented in the previous section. The battery charging current for walking and running will be discussed.

Figure 8 shows a fragment of the battery charging current while walking, using the configuration and power management circuitry showed in Figure 7, and Figure 5. Because of the nature of the harvester, the battery charging current is fluctuating. The current shown is for an average walking speed of approximately ~5.0 km/h for a male weighing approximately 75 kg. The average battery charging current is equal to 54 µA. The system harvests approximately 0.6 Joule per hour of walking.

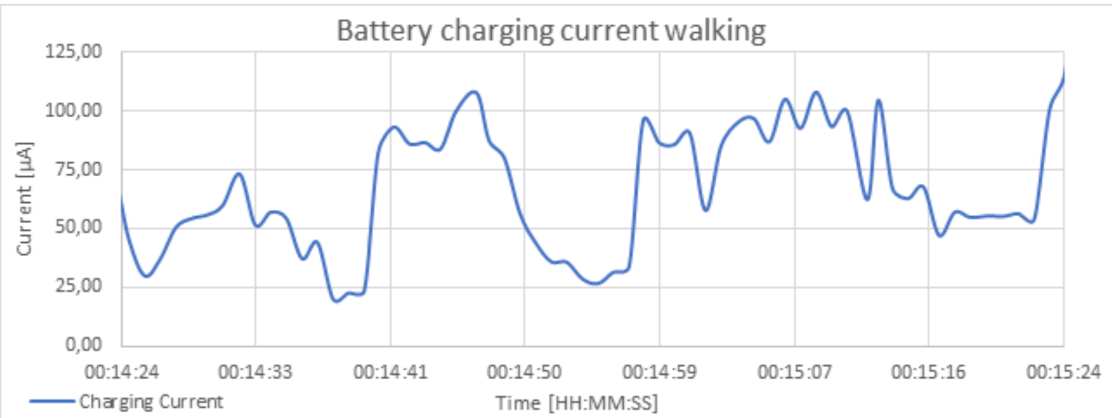

Figure 8: *Battery charging current while walking.*

Figure 9 shows a fragment of the battery charging current while running using the configuration and power management circuitry showed in Figure 7, and Figure 5. The current shown is for an average running speed of approximately ~10.0 km/h for a male weighing approximately 75 kg. The average battery charging current is equal to 106 µA. The system harvests approximately 1.2 Joule per hour of running.

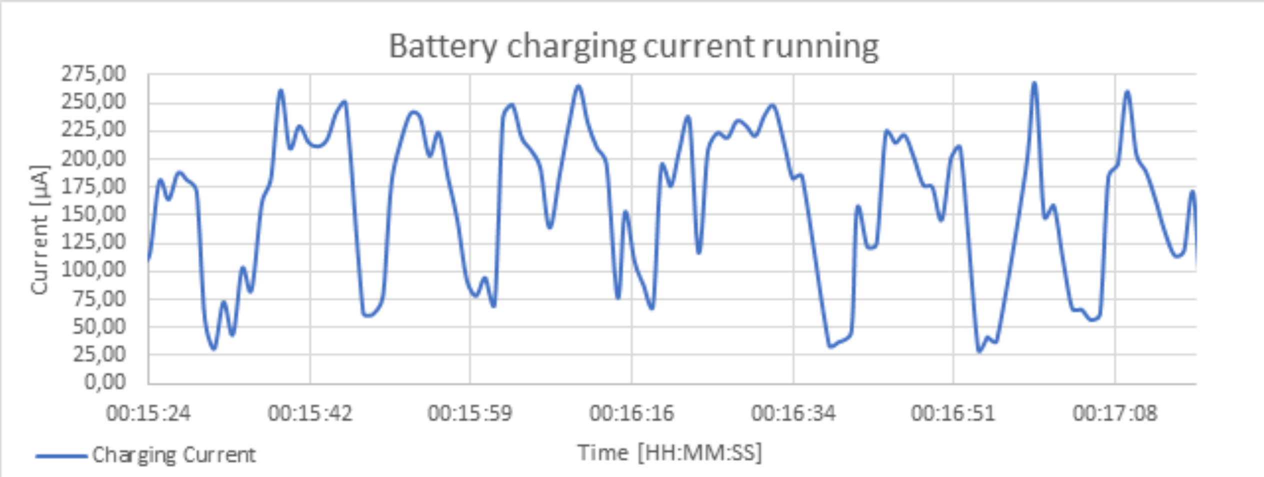

Figure 9: *Battery charging current while running.*

6. Nowi Smart Footwear Power Profile

This section presents the power consumption of the system. The power consumption of the system is determined by the sampling frequency of the Microcontroller Unit (MCU) in the BLE module. The sample rate of the MCU is determined by the settings for the Real Time Counter (RTC). The BLE module wakes up after an RTC trigger to take a sample, and perform a flash memory write cycle if the internal buffer is full, and goes back into sleep after. A higher sample rate corresponds to the MCU waking up more often, and the flash memory performing a write cycle more often, which increases the power consumption of the entire system.

Figure 10 shows the distribution of the power consumption of the system at a sample frequency of 20 Hz. The power profile and the average power consumption of the Nowi's Smart Footwear prototype is characterized using Joulescope Direct Current energy analyzer. Figure 11 shows the power profile of the system when the MCU wakes up to take a sample and goes back to sleep after the sample is taken. The system consumes approximately 15.95 µJ when the MCU wakes up, takes a sample, and goes back into sleep.

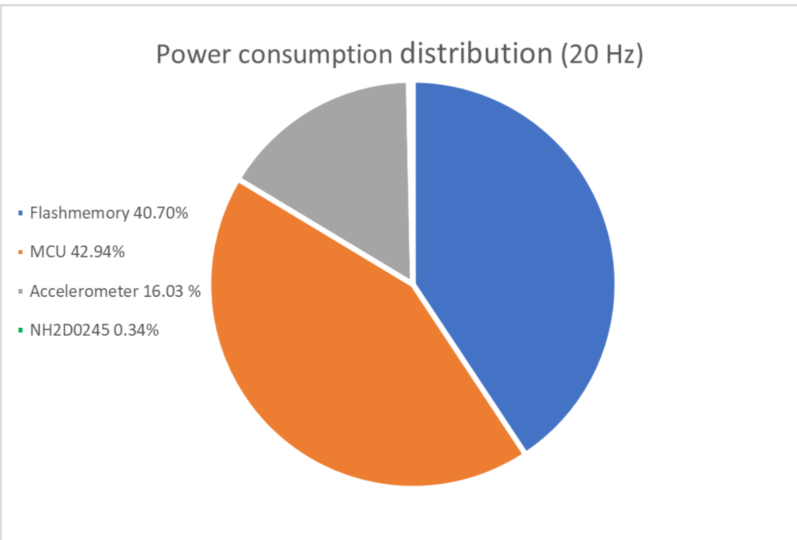

Figure 10: *Power consumption.*

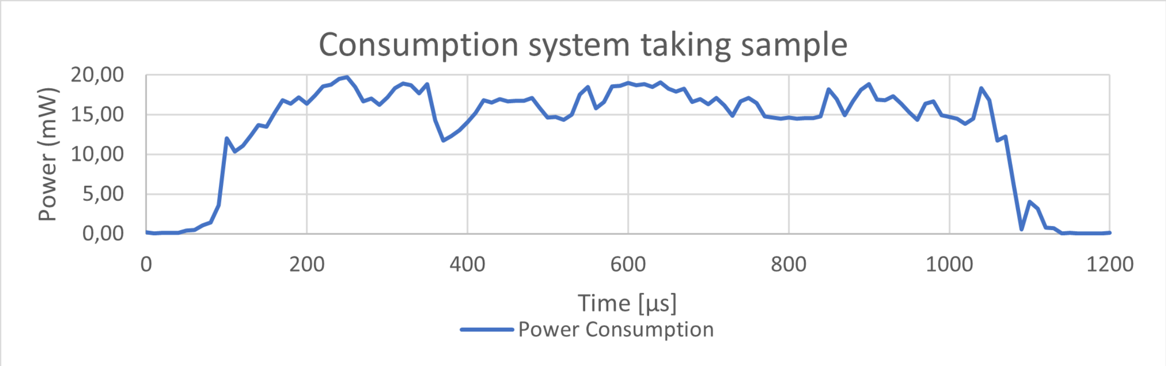

Figure 11: *Power profile system taking sample.*

Figure 12 shows the power profile of the system when the MCU wakes up to take a sample, writes the buffer into the flash memory, and goes back to sleep after the flash memory write cycle is performed. The system consumes approximately 1.67 mJ when the MCU wakes up, takes a sample, writes data into the flash memory chip, and goes back into sleep.

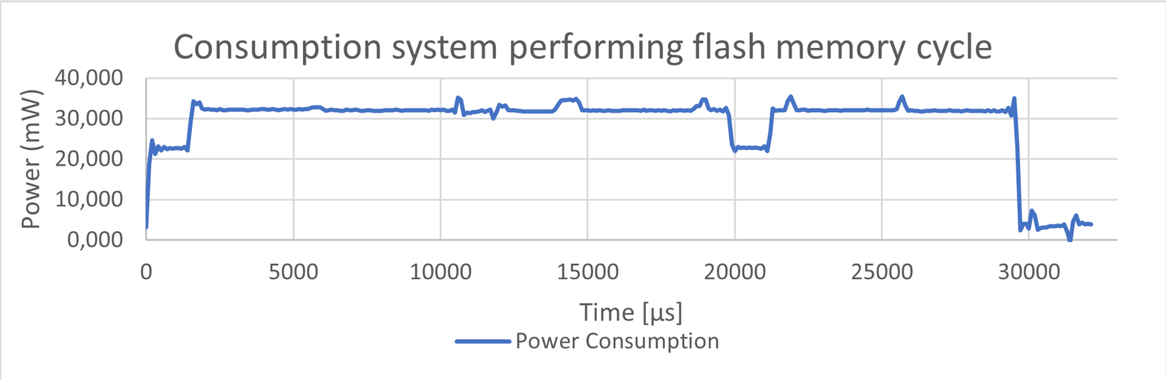

Figure 12: *Power profile system performing flash memory cycle.*

7. Nowi Smart Footwear Prototype Battery Lifetime

This section presents the battery lifetime of the Nowi Smart Footwear system with running energy harvesting. The power consumption of the system is primarily determined by the sample rate of the MCU to the sensor. This determines the interval between the MCU being awake and asleep. Table 1 shows the power consumption values, and battery lifetime for different sampling frequencies. The battery lifetime includes the energy harvesting from running.

SAMPLING FREQUENCY [Hz]	POWER CONSUMPTION SYSTEM [mW]	BATTERY LIFETIME AT 65 mAh [HOURS]
5	0.31	Energy Autonomous
10	0.51	1016
15	0.70	510
20	0.89	341
25	1.07	259
30	1.33	193
40	1.66	145

Table 1: *Power consumption and battery lifetime.*