ENERGY HARVESTING POWER FLOWER BELL – A CYBERNETIC SOUND INSTALLATION DRIVEN BY A DIRT-BATTERY

Josef Schauer
TU Graz
josef_s@sbox.tugraz.at

Winfried Ritsch
KUG Graz
ritsch@algo.mur.at

Lothar Fickert
TU Graz
lothar.fickert@tugraz.at

ABSTRACT

This work describes the art-driven development of an energy harvesting system in sound installations. The used energy source is a dirt-battery. It is built by digging a piece of copper and a piece of zinc in a soil. Sound is generated when there is sufficient energy to trigger a bell. In the described sound installation, such a system looks like a flower and the bell represents its bloom. With its *roots* (electrodes) dug into the soil, it generates electrical energy to make sound. It is shown that this concept works. It is possible to make sound by dirt-energy. In a further step, many of such devices which are called Power Flower Bells (PFBs) should be spread in a meadow, communicating with low-power Radio Frequency (RF) technology, realizing musical compositions.

1. INTRODUCTION

The project was initiated by the artist Winfried Ritsch. His idea is to realize a cybernetic flower meadow, made up by a field of robotic flowers as a kind of cybernetic organism. These flowers should be powered by dirt-batteries and/or other energy sources [1]. Because other sources are well known and documented, the motivation of this project is to run the PFB just with a dirt-battery. Additional sources, as long as they have a matching ($\leq$3 V) Direct Current (DC) output, can be applied easily in order to fulfill the artistic vision of obtaining a robotic device that behaves quite like a natural flower because it needs water, light and space. There is a direct link between the energy they can harvest and the musical output they deliver. The musical performance depends on the state of each flower.

Thinking further this approach, the artist expresses the perception of the Power Flower Bells by visitors and gardeners as an independent life-form which is nourished by the environment [1]. A dirt-battery needs to be watered, otherwise its output gets a lot weaker and the PFB could stop running its Real Time Clock and Calender, which is the time basis for activities like clinking the bell. Also the RF communication uses this time base to be synchronized.

1.1 Problem Statement

Nowadays, there are some projects working with dirt-batteries, like the Soil Lamp [2]. The Soil Lamp is based on several cells of dirt-batteries connected in series to obtain a higher output voltage. To run a PFB, just one cell is needed which has a measurable output of about 0,8 V. The multiplication of the surfaces of the electrodes in this cell comes up to a parallel connection of many cells. For the here presented project it is essential that the installation of a flower meadow with many PFBs is an easy task. It is much less work to install one cell than to install many cells, especially because the zinc-halfs and the copper-halfs have to be separated from each other in one cell to prevent electron flow through the soil. The use of just one cell requires a circuit which is enable to convert the low voltage to a higher value, because even low-power micro-controllers need a minimum voltage of 1,8 V. To buffer energy for energy-intensive tasks like ringing the bell or RF-activities, an energy storage like a supercap is needed.

1.2 Scientific Interests

Because of the modular flexibility, the access to solutions for realizing energy harvesting sound installations or sensor/actor nodes increases by analyzing the technology. The great advantage of energy harvesting systems which is noticed by the industry is the fact that there are no costs for changing batteries any longer. Obviously, most of artists doing sound installations based on unwired devices would appreciate this quality too.
The knowledge of how to apply energy available in the direct environment of a system to build up a sound installation which is networked via RF can help to develop a wide spread of useful systems which do not just serve as sensors like as already applied in a lot of cases in industry, but also as actors which of course can just act when there is enough energy available. For a swarm or a cluster of items, this also requires research on how they can communicate. Another motivating fact is that by running a copper-zinc galvanic element in a copper-polluted soil – as you can find it for example on many traditional wine yards – the zinc will be left in the soil and the copper will be united with the copper-electrode, so the Power Flower Bell represents a nice-sounding detoxification method for copper-contaminated soils.

2. OVERVIEW

A block diagram of the system is shown in figure 1. It shows up the essential blocks of the PFB. The low output voltage of the dirt-battery (about 0,8 V) has to be converted to a higher level to enable the rest of the system to work properly. This happens in the power handling block. The increased voltage is loaded to a storage element, currently a supercap with a capacity of 10 mF is in use.
A dirt-battery can be too weak to even rise the voltage in the supercap to 1,8 V, which is the minimum voltage for getting the micro-controller started. When the dirt-battery is strong enough, the micro-controller starts, but immediately a sleep-instruction is given by the firmware.
When the voltage in the supercap reaches 3,5 V, the VBAT_OK pin of the bq25504 rises to high. Since this pin is connected to an interrupt-pin of the micro-controller, this one wakes up, acts if necessary and changes to sleep mode again. It is essential that the micro-controller spends as much time as possible in sleep mode to work efficiently.
The Real Time Clock and Calender (RTCC) implemented on the micro-controller keeps running all the time and means the time basis for all actions of the device.

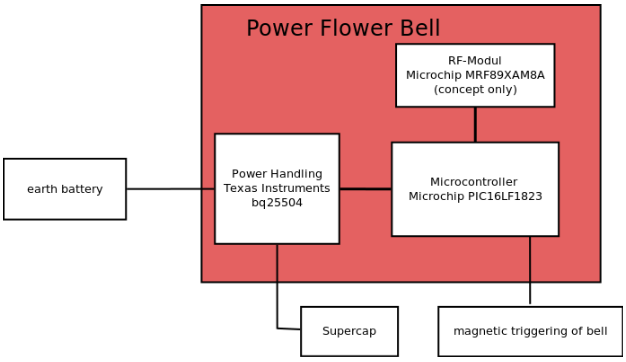

Figure 1. Block diagram to summarize the Power Flower Bell (PFB)

3. ENERGY GENERATION

Since the used hardware is able to handle various types of electrical energy generators, some of them are described in the Master Thesis [3], but this work is focused on the dirt-battery as an energy source.

3.1 Redox Reaction

Oxidation is a chemical reaction in which a material electrons are abstracted, reduction is a chemical reaction in which a material electrons are added. Redox reaction is the term for a chemical reaction in which electrons from one material are transferred to another one. This results in a change of the oxidation number of the materials involved in the reaction. The transport of electrons is the most important effect in a redox reaction, but besides, there can occur a transfer of atoms and ions. The reducer is the electron donor, and the oxidizer is the so-called electron acceptor.

By putting a piece of zinc in a solution with Cu^{2+} ions, a spontaneous redox reaction in which metal copper is sedimented on the piece of zinc, is obtained. The zinc in this process is dispersed.

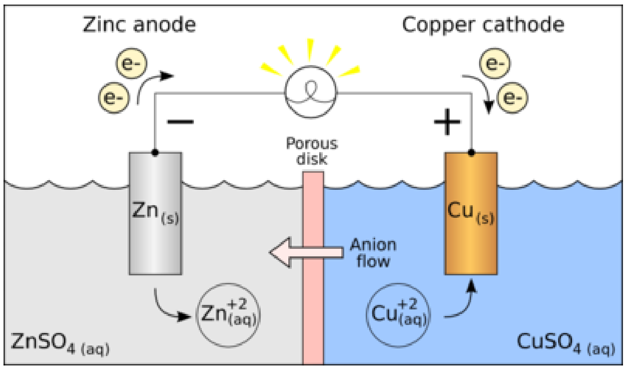

Figure 2. Galvanic cell [5]

In figure 2, you can see a galvanic cell which works with the same redox reaction of zinc and copper, but there is no direct conductance between the zinc and the Cu^{2+} ions. In one tank, the zinc electrode is in contact with the Zn^{2+} ions, while in the other one, the copper is in contact with the Cu^{2+} ions. That is why the reaction can just take place due to electrons moved from one electrode to the other by connecting them externally. By separating the reduction and oxidation half-reaction, electrons are forced to move externally. The electrode on which the oxidation takes place is called anode and the one on which the reduction is situated is named cathode. The oxidation of the zinc in the one half-cell leads to an increasing concentration of the Zn^{2+} solution and a decreasing mass of the zinc electrode. In the other half-cell, the reduction of copper leads to a decreasing concentration of the Cu^{2+} solution and a mass growth of the copper electrode [4]. Materials like platinum or graphite permit electron migration without mass losses. To keep the reaction running, the solutions have to be kept electrically neutral. The overload of Zn^{2+} has to be compensated by positive ions that leave the half-cell, or negative ions have to be added. In the other half-cell, the reduction of Cu^{2+} ions in the solution means a deficit of positive charges in the solution. This has to be compensated by adding positive ions or removing negative ones.
For this reason, a diaphragm, which allows ions to move from one half to the other but prohibits electrons to pass is necessary. Such a diaphragm can be a porous disk or – in the case of the dirt-battery – a pot made of clay.

3.2 Dirt-Battery

A dirt battery is nothing than a galvanic cell. The soil acts as the electrolyte. A dirt-battery was first shown by Alexander Bain in 1841 [6]. The output power of an earth-battery is not constant, it depends on factors like the connected load, the state of the electrodes, the state of the soil, in which they are planted in, as the distance between the electrodes. *Earth-battery* is another synonym for naming the same thing as *dirt-battery*.
Some humidity in the soil is necessary, so a PFB *living* indoors without being watered sometimes might not make any sound.

Figure 3. Dirt-battery *photo: Christoph Staber*

Figure 3 shows the used dirt-battery. It is built by a bucket made of plastic and filled with flower-soil. The copper electrode is a shield with a length of 70 cm and a width of 20 cm. In the center of the bucket, a flower pot made of clay is placed. This represents a diaphragm to isolate the two electrodes electrically. In the center of the pot, the zinc-electrode which exists in a solid block of zinc, is dug into soil.

The power that can be exploited from such a source strongly depends on the load connected to it. That for, the behavior of the dirt-battery is investigated by connecting resistors with different values between 1 Ω and 10 kΩ to it. The obtained curve can be seen in figure 4. Obviously, there is a specific resistor that permits the maximum output power. A dirt battery delivers the maximum output power when the connected load leads to an output voltage which is the half of the open-circuit voltage. This operation point is called *Maximum Power Point*. A theoretical explanation for this is given in [3].

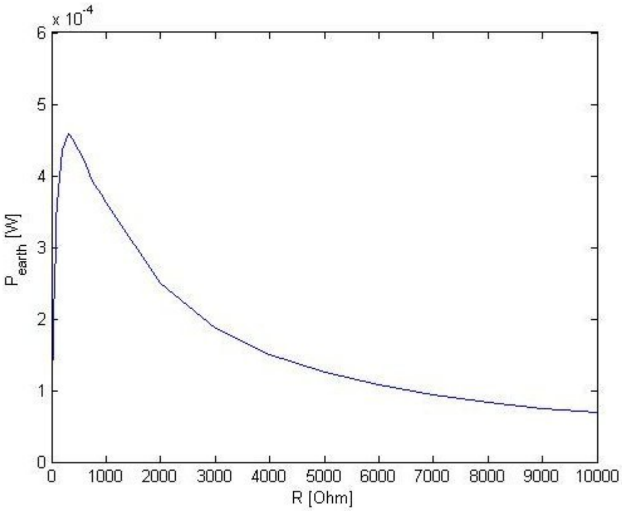

Figure 4. Sweep over resistance loads applied to the dirt-battery

3.3 Power Management

The low output power of the dirt battery is converted to 3,6 V by a Texas Instruments bq25504 Ultra Low Power Boost Converter with Battery Management for Energy Harvester Applications.

An important feature of the bq25504 is Maximum Power Point Tracking. This technology is commonly used in systems supplied by photo voltaic. The relation $\frac{V_{\text{out\_oc}}}{V_{\text{out\_MPP}}}$ can be set-up dimensioning two resistors. As mentioned in subsection 3.2, for the dirt-battery, this value is $\frac{1}{2}$.

The chip permits control over the storage element. The lower limit of the battery voltage, as the upper limit can be programmed. Further, there is a pin that signals a battery ready status at a programmable voltage measured at the supercap. This pin is connected to an interrupt pin of the micro-controller.

3.4 Effects on the Environment

The dirt-battery is thought to be applied in a free-field scenario. The intention is, in the best case, just to put a piece of copper and a piece of zinc into the soil and start harvesting electrical energy.

In a society in which the ecological footprint is becoming a more and more important factor in making decisions for people in their buying-behaviour, as in times of decreasing availability of resources on one hand, but increasing demand for resources on the other hand, the question has to be asked how ecologically sense- or harmful a technology is.

An article by Greenpeace [7] calls attention to this topic, especially when copper is used. It is not broken down but stays in the soil and does harm the biodiversity. For example, the earthworm is banished by copper. In France, 1885 copper was becoming a common fungicide. Up to now it has been known as an almost perfect substance for this application. Especially ecological wine farmers in the European Union are very dependent on the use of copper, since they are not allowed to use other fungicides. Mainly it is applied as copper-sulphate of which 3 kg/ha are allowed to be applied every year in Austria. In the 1960 of the last century, in some zones up to 60 kg/ha were applied annually.

The dirt-battery would leave zinc in the earth, while copper is brought from the soil to the copper electrode. That means, a dirt-battery could accumulate copper from a copper-polluted soil, lowering the copper-concentration in the contaminated soil.

4. NETWORK

An important feature is the low-power RF module, with which the PFB is equipped. It is a Microchip MRF89XAM8A 868 Hz Ultra-Low Power Sub-GHz Transceiver Module that includes a transceiver controller, peripherals and a Printed Circuit Board (PCB) antenna. Being synchronized by a Real Time Clock and Calender (RTCC) implemented on the micro-controller, the devices can communicate with each other. The synchronization is necessary, because RF communication is an energy-intense process and that for it should be inactive most of the time. At certain time-slots, the PFBs are enabled to receive data and exchange information. In order to be able to realize compositions, a newly planted flower starts sending data at defined time-slots. It starts with the lowest transmitting power. After sending a request to its environment, it waits for an answer of another PFB. If there is an answer, an ID of the other device, as the transmitting power necessary for contacting it are stored. Additionally, the Received Signal Strength Indicator feature of the low-power RF module permits an estimation of the distance to the device that has sent the response. Of course, more data, for example the key tone of the bell of each PFB can be stored. Like this, knowledge of the environment is earned. This knowledge can be exchanged again with other PFBs which are in the coverage of each other. So, if there is enough memory, a PFB can reproduce how the meadow is organized in a plane. The choice to use a module that comes up all-in-one with a PCB antenna was made because exhaustive development of the low power RF circuit would mean a lot of additional effort. The micro-controller controls the module by Serial Peripheral Interface (SPI).

5. COMPUTING

All the computing necessary is done by a micro-controller. In the first development step, this is a PIC16LF1823 micro-controller from Microchip®. The controller represents a minimalistic solution in terms of the resources of the device as its pin count (all in all 14 pins). The advantage of this choice is little energy consumption. Very important in the context of the Power Flower Bell is the current in sleep mode, because the device will spend most of the time in this mode. Powered with 1,8 V, the sleep current is rated with 20 nA and the operating current with 34 µA@1 MHz.

6. SOUND GENERATION

Electric generation of sound is a critical task in terms of energy consumption. Common loudspeakers have a weak efficiency, particularly small speakers [1]. Bells appeared the first time about 5000 years ago in Asia [8]. Up to today they are used to send acoustic signals to wide areas in many cultures. A big effort using a bell is that it produces a quite loud output with just a single hit on it. The hit corresponds to a control-signal which ideally looks like an impulse, but since the used motor is not ideal, it needs a control signal which looks like a unit step stopped after a small period of time (about 1 s). Because of this small period, the hammering on the bell is supposed to be very energy-efficient compared with loudspeakers, for which further amplifiers would be necessary as well.

For this reason, the simple method of bells for sound generation was chosen for the Power Flower Bell.

In future development steps, small loudspeakers might be implemented. The additional computing power that is necessary to reproduce music represents a challenge. In the case of a bell it is just a variable that has to be set if a current through the coil of the used motor is desired.

6.1 Pipe Bells

Pipe Bells were chosen by Ritsch because of it's sound. Hueber [9] and Rossing [10] described the bending vibrations of circular cylinders as not harmonic, they rather produce "nearly harmonious" partials. Hueber measured that the fundamental frequency one hears, physically is not present but rather is formed psychologically. Fletcher and Rossing documented the use of Flugges formula to pipe bells [11]. They also discussed the model of the virtual pitch which is important in the context of bells, because all of them show the feature of a strike tone. The strike tone is heard more or less clearly, depending on the quality of a bell. By convention, the part tones of a contemporary church bell are intended to come as close as possible to the frequency ratios 1:2:2,4:5:6:8, the higher part tones are not defined that strictly. Although the ratios 1:2:3:4:5:6:8 and 2:4:6:8 are quite familiar, the minor third between 2 and 2,4 does not fit into the harmonic series nor the series. The strike tone is the *holistic* pitch that a sound of a bell is associated by the ear immediately after the bell is striked. It is not possible to find a period of a fundamental frequency in the time signal or in the part-tone spectrum. The strike note is the most prominent one of multiple pitches that are elicited by a bell sound. Terhardt [12] explains the assigning of several pitches to just *one* pitch with the hierarchically organized perception of humans. An object may appear as a collection of multiple elements (spectral pitches) at the bottom of the hierarchy but may be represented by just one perceptual object (virtual pitch). The pitch ordinarily heard, is not dependent on the audibility of the fundamental. The auditory system extracts the fundamental from a range of the Fourier spectrum that extends above the fundamental [12].

6.2 Playing Music

Ritsch first was thinking of a lot of small devices that generate sound and are placed in a quite silent environment, as a meadow for example. The devices should act like musicians accumulated to a swarm. He describes the sound they would produce as an *endlessly distributed composition in time and space*.

For example, the PFBs can trigger their bells in spacial propagating waves. Also the performing of rhythmical dialogues and complex algorithmic interactions are possible [1]. Further Ritsch mentions the influence of former projects like *The House of Sounds*. Actually, *The House of Sounds* is a computer program that permits listening to a *sound world* built by *soundobjects* which are stored on computers. This computers are part of a *data-network*. The *soundobjects* age, can move from one computer to another one without external input, form groups, duplicate or die. Their existence is based on computers running the *House of Sounds* program connected to a data-network [13].

The clinking of the bells should have the opportunity to become a kind of spacial composition. Rhythmics and dynamics, as different bells for different flowers are the ways to express musical structures [1]. With different types and sizes of bells, harmonic variations can be performed. Playing few or no tones for some while enables a PFB to collect

Figure 5. Christmas bell that helped to estimate the required energy

more electrons into the supercap, as long as this one has enough capacitance. Later, the flower can realize faster rhythms, because there is more energy available before the device has to change to its energy-harvesting mode. A human can manipulate the performance by updating one Power Flower Bell which then signals to its neighbors how to continue, the neighbors send this information to their neighbors and so on. In future, it is also planned to construct different Instruments and sound-generators. For example, a chord can easily be used by hammering on it. A vision is to realize an orchestra with drums, strings and bells played with energy that comes from dirt-batteries, photo voltaic cells and similar sources.

6.3 Interfacing to the Environment

Applying different energy sources and sensors, the Music played by a PFB will be dependent on the surrounding. As mentioned in 3.2, in the current version a PFB for example needs water. Without watering it, it will get weaker and weaker, which in the actual programmed setups means, that the hits on the bell occur with more temporal distance, because it takes longer to collect energy. Imagine a PFB driven by photo voltaic, *living* outdoors: During a sunny day, it might play very fast variations, but during the night it will not be able to ring any time. In another way sensors could be applied, which measure parameters like the temperature of the air, loudness etc. The artist then is free to determine, in which way the measured signals will be used to manipulate the musical performance of one or more PFBs.

6.4 Estimation of Energy

The kinetic energy which is necessary to be given to a bell in order to produce a well hear able sound was estimated doing an experiment with a Christmas bell as shown in figure 5.

By measuring the mass of a clapper (m), mounting it to a piece of twine, deflecting it to a certain height (h) and releasing the clapper from this height, the energy stored in it in the moment when it touches the bell is W_{kin}.

$$W_{\text{kin}} = W_{\text{pot}} = m \cdot g \cdot h \tag{1}$$

Because all losses are neglected, the potential energy is supposed to be the same as the kinetic energy in the moment of the impact between the clapper and the bell. It was possible to hear the bell at adequate loudness when the clapper with a mass of 5 g was deflected to a height of 5 cm and released. This means, an energy of 2,9 mW was given to the bell by the impact. This value was important to get an idea for dimensioning the whole system.

7. IMPLEMENTATION

The triggering of the bell is implemented by an extra n-channel Metal Oxid Semiconductor Field Effekt Transistor (MOSFET) on the PFB board. Its gate is connected to a General Purpose In-/Output (GPIO) of the Micro-controller. Configured as an output, it can be used to control the hammering of the clapper on the bell.

The actor in the first version is a low-cost vibration motor like used in mobile phones. On its spindle, a thin piece of stiff wire is soldered. The interior of a luster terminal is fixed on this wire. Different sounds with one bell can be obtained by the firmware, which controls how long the motor is connected to the supply voltage stored in the supercap. Other possibilities are varying the point on the wire where the luster terminal is mounted as the distance to the bell and the point of the bell where the clapper (luster terminal) hits the bell. In future works, this parameters should be investigated. Figure 6 helps to get an idea of how a Power Flower Bell can look like. This device was built together with Winfried Ritsch.

Figure 6. The first sounding Power Flower Bell *photo: Christoph Staber*

8. CONCLUSIONS

The work on the presented project showed that, in principle, it is possible to run low-power electronic devices like sensors or actors by a dirt-battery. A PFB device can be seen as such a device. Even if the amount of extracted energy is quite low, it can be a model for other applications. The dirt-battery, in its current state, can be developed further by optimizing the composition of the soil and the used diaphragm. Moreover, there might be applications, where galvanic energy is available as an unused source.

This work is one of a few available publications describing dirt-batteries. Much of the information about this topic found in the Internet is not scientific but sometimes even esoteric. All other systems found are driven by a serial set up of dirt batteries. The here presented system is based on *one* single cell of a dirt-battery, which is much easier to install.

The designed circuit can also be powered by many other kinds of DC low-power sources. There are certainly new possibilities for artists who want to realize a wireless networking, energy harvesting driven sound installation.

The integration of the RF part into the PFB circuit was not done during the project. However, the basics of this part of the system are described in the present document.

Even if the dirt-battery is not yet optimized, the functionality of the whole system could be shown.

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