Load Monitoring for Orthoses with Energy Harvesting Powered Sensor

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Abstract: A new self-powered sensor with wireless connectivity is presented. The system is powered by piezoelectric energy harvesting from human motion. It can be implemented for example into orthoses, medical walking aids, shoes or prostheses. Force sensors measure the weight bearing on a lower limb. The collected data is processed and transmitted to a smartphone or computer using Bluetooth Low Energy (BLE). On the receiving device, the data is analysed and visualized and can provide information for patients and physicians to support healing processes. Initial tests show that the harvested energy is sufficient for a stable operation of the embedded system.

1 INTRODUCTION

Patients with injuries on lower limbs need to reduce the weight bearing on the leg or foot during recovery. Over-straining can cause a delay of the healing process or even new injuries. However, it can be difficult for a patient, to estimate the applied weight. An appropriate tool can help monitoring with continuous measurements using force sensors. It can trigger a warning, if overstraining is imminent. Built into a cast or an orthosis, a small and light device does not interfere with the patient in daily life. In general, the possibility to monitor a patient constantly over a period of time with small effort for both patients and physicians offers new possibilities in diagnostics or in supporting treatment.

Usually wearable devices are powered by a rechargeable battery (Merrett et al., 2010). This increases weight and size and can make the use of the product as well as its designing more complicated, for example with regard to waterproofness and reliability. In addition, the materials used for the production of batteries, as well as their disposal at the end of the product lifetime poses a potential risk for the environment.

Instead of using a battery, the energy needed to operate a wearable device can be harvested from the environment. Typical sources are light, body temperature or mechanical forces. In recent years,

there was rapid development towards more energy efficient devices. Therefore, there are more and more applications, where energy harvesting is a possible solution.

By using energy harvesting as a source of energy, the threshold for application is lowered compared to using a battery or accumulator. The user does not need to perform maintenance tasks like changing or charging a battery before use, but can instead put the device into operation immediately. This makes such a device convenient also for less technically oriented users, for example elderly people. In addition, it increases safety and reliability of the device since it is not dependent of a limited energy supply.

2 PIEZOELECTRIC ENERGY HARVESTING FROM MECHANICAL FORCES

The piezoelectric effect is used in sensor technologies in various applications. When piezoelectric materials are deformed, they produce a voltage proportional to the applied force. The preferred way to use the piezoelectric effect in energy harvesting is to exploit vibrations with a piezoelectric oscillator. When operated at resonance frequency, it can produce a decent amount of power.

However to keep a piezoelectric oscillator at resonance frequency, a very steady movement or vibration is required, which in reality is often not the case. The power output decreases drastically, if the oscillator is not in resonance.

Figure 1: Impact force on the base of an orthosis, used to deform the piezoelectric element (Source: Colourbox, modified).

In this application, energy is harvested from human motion like walking. Because of the low speed of the movement and its inconsistency, resonances cannot be exploited. Instead the events of force impact have to be treated as single events, from which as much energy as possible has to be harvested.

3 OVERALL CONCEPT

The presented prototypical system showed in Figure 2 consists of an energy harvester, a microcontroller with a BLE transmitter, a force sensor and an Android application (Stahel and Hermann, 2017).

In the energy harvester, a piezoelectric element transforms mechanical forces into electric energy. The energy is stored in a capacitor, which is monitored by an energy management unit. A step down converter provides the voltage level for the microcontroller.

At each program cycle, triggered by the piezo harvester, the microcontroller evaluates the force-sensing resistor. This data is then sent via BLE in advertising mode and is received and visualized by an Android application.
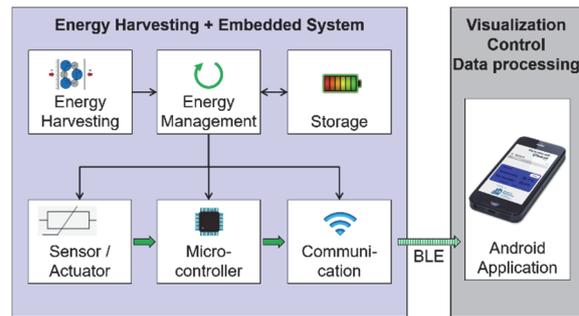

Figure 2: Overall concept of the presented solution.

3.1 Energy Harvesting

A piezo buzzer (Figure 3) is usually used as an actuator to produce a sound signal by applying an AC Voltage in a particular frequency. It is used in cheap speakers to produce warning signals or other low quality sounds. Thanks to their simple structure and mass production, they are very affordable.
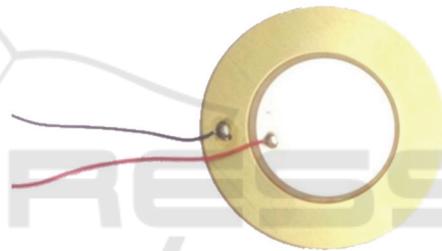

Figure 3: Standard piezo buzzer used for the application.

In this application, a piezo buzzer is implemented as a generator. By deforming the buzzer a voltage between the piezo ceramic layer and the brass base is produced that can be harvested by a suitable circuit.

Ideally, the piezo buzzer it is placed at a position, where the first force impact occurs. For an orthosis, the optimal position would on the bottom side (Figure 1), for crutches, the buzzer can be positioned at the tip or inside the joint in the shaft.

At every step, the device uses the first impact on the piezo buzzer as a trigger point to wake up the microcontroller and start the measurement routine. For that purpose, a high-pass filter is connected to the piezo buzzer to register the rising voltage and to provide an input signal to the comparator of the microcontroller.

The energy yield of the piezo buzzers was evaluated in laboratory tests. Depending on the preload of the storage capacitor, an energy yield of up to 3 mJ from a single stroke could be achieved

(Figure 4). Two or more piezo buzzers can also be stacked to increase the energy yield.

For these measurements the piezo buzzers where connected to a full bridge rectifier consisting of BAT54 diodes and to a capacitor. The voltage level of the capacitor after each pulse was evaluated and the resulting energy calculated.
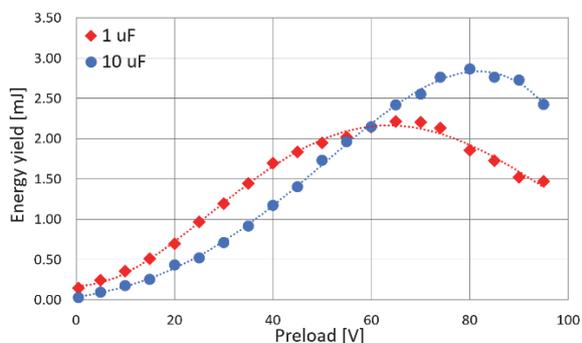

Figure 4: Energy yield of piezo buzzers at different preloads and with two different storage capacitor sizes.

The main element of the harvester circuit is an LTC3588 chip from Linear Technology. It is a specialized chip for energy harvesting from piezoelectric sources and consists of a rectifier and an efficient buck converter to convert the input voltage of the piezo buzzer into a stable output of 1.8 Volt. The input voltage of the LTC3588 is limited to 20 Volt. Before converting, the energy is buffered to bridge idleness.

3.2 Microcontroller and Sensors

Based on (Gugg et al., 2016) an NRF52832 microcontroller by Nordic Semiconductors was used as a basis for the embedded system. It contains an ARM Cortex M4 32-bit processor as well as a 2.4 GHz transceiver for BLE. To measure the weight, force sensing resistors where implemented. The microcontroller can evaluate them using its 12-bit analog-to-digital converter (ADC).

With an additional ADC measurement, the voltage level of the storage capacitor is monitored. Depending on the available energy in the storage, the collected data is sent via BLE. In continuous operation, it is possible to evaluate the sensors and send the data at every step, thanks to very low power consumption.

The ADC measurement, including initialization, data acquisition and data transfer with Direct Memory Access (DMA) consumes only 1.1 µJ. Sending the data in advertising mode on three channels uses around 20 µJ at a transmission power

of 0 dBm. The transmission power was chosen to ensure a stable communication, but can be reduced to save energy. Standby phases of the microcontroller in between two steps consume 8.1 µJ per second.

4 PROTOTYPE

A prototypic implementation of the autarkic sensor was implemented. It consists of a harvester system, a microcontroller with BLE transmitter and force sensing resistors (Figure 5).

The system was fitted into an insole. Apart from monitoring weight load, this device demonstrates a different potential application. By spreading the force sensors on the sole, the device measures the weight distribution. It could be used for orthopedic gait analysis.

Figure 5: Overview over prototypic system. The piezo buzzer is placed inside an aluminum housing.

The system contains no moving parts. The most stress is on the piezo buzzer that has to be deformed at every cycle. This could potentially damage the piezo-ceramic layer on top in the long term. To prevent this, the piezo buzzer was placed inside an aluminum housing. This allows limiting the maximal bending to 2 mm. The power output is only marginally affected this limitation. It is also largely independent of the weight of the user. The piezo buzzer can be bent with little force.

The complete system with piezo buzzer, four force sensors and the microcontroller circuit board can be fitted on an orthosis (Figure 6). Miniaturization can presumably be achieved by a factor of two or more, so that the autarkic sensor system can also be used in a more limited space like

crutches. Introducing additional sensors or circuitry is possible, provided the energy budget is taken into account. At a weight of only a few grams, the device does not bother the wearer during use.

Figure 6: View of a possible mounting of the system on an orthosis. The piezo buzzer and sensors are placed at the bottom, the microcontroller is mounted on the side (Source: Colourbox, modified).

The bill of material of the prototype device, excluding force sensors, adds up to around 40 USD. This includes the piezo buzzer that is very affordable at a price of only 2.80 USD. The used force sensing resistors cost an additional 20 USD per piece.

4.1 Android Application

The sensor system sends the data of the force sensors, the measured voltage value of the storage capacitor and a step counter value using advertising mode. Each packet has a length of ten bytes and is sent three times successively. For processing and visualization, the data can be received by an application that runs on any Android smartphone capable of BLE.

The Android application scans for advertising data, recognizes the packets by their ID and extracts the sensor data.

The application uses calibration data of the force sensors to scale the measured values and display their relative distribution by using text and color. The step counter data and the current energy storage level is also displayed (Figure 7).

To display the current weight load in total the application can be modified. With the weight of the person and the calibration data of the force sensors, the total load can be calculated and displayed both graphically and textually. The step counter would be
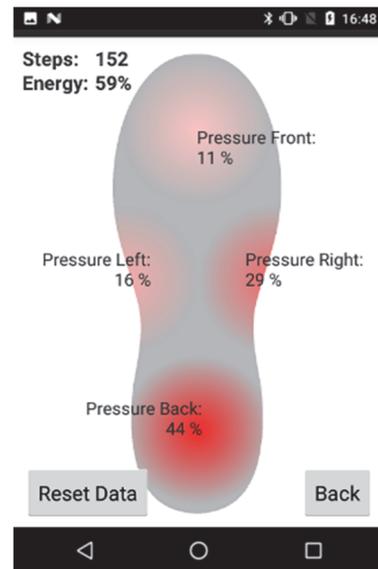

Figure 7: Sample view of the application. The color and percentage value indicate the current weight distribution on the foot.

of marginal interest in such an application and could be omitted.

Signaling imminent overstraining could also be done in a different way than via an Android application. An acoustic or a tactile indication could be implemented, depending on the use case and energy budget. This way, the inhibition threshold can be lowered further to make the device accessible to less technically oriented users who might have difficulties to use a smartphone.

4.2 Performance

When the system is fully started up, it can be sustained with an energy pulse frequency from the piezo buzzer of less than 1 Hz, which corresponds with a normal walking speed of an injured person. Data acquisition, processing and transmitting and the standby of the microcontroller consume around 30 µJ at each cycle. The harvesting system provides around 90 µJ of energy at each pulse on average (Figure 8, right side).

In conclusion, the system can store up to 60 µJ on average at each pulse and can thus sustain operation in standby for a certain time, while no energy can be produced. The storage capacitors will then eventually discharge due to leakage.

Starting up the embedded system consumes around 100 µJ and can be done after about five pulses from the piezo buzzer, as laboratory tests have shown. The amount of energy produced is

significantly smaller during the first few pulses with empty storage capacitors and improves with increasing charge of the capacitors as shown in Figure 4. Therefore, the initial startup of the system poses a challenge. This is indicated in Figure 8 on the left side.
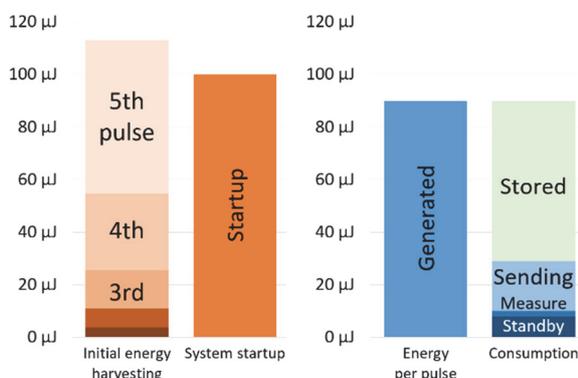

Figure 8: Comparison between generated and consumed energy. Left: Startup process (approximated); right: continuous operation.

To improve the start-up procedure, an array of storage capacitors is introduced (Figure 9). It consists of three different capacitors in parallel that can be enabled according to the current operating state. At start-up, a small capacitor is used to provide the buck converter with a high voltage as quickly as possible. For continuous operation, additional capacitors are activated to provide enough storage. Due to the charge equalization that takes place when a new capacitor is activated, the larger capacitors do not need to be charged from an empty state, which improves efficiency significantly.
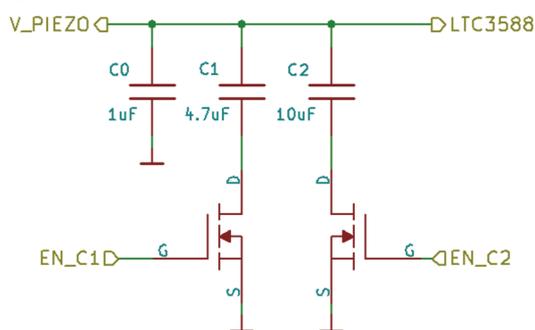

Figure 9: Schematics of storage capacitor array.

5 APPLICATIONS

The presented system provides a wide array of possible applications. Examples are medical walking aids (Merrett et al., 2009), supports, rails or prostheses. It can be implemented to measure the applied weight bearing on an injured lower limb after a fracture or a cruciate ligament tear for example. This way the system can help to improve the healing process and prevent damages from overstraining.

By recording and live reporting data about the weight distribution on the foot, the autarkic sensor system can be used as a tool in orthopedic gait analysis (Hadi et al. 2012). For this, several force sensing resistors can be placed on different spots on an insole. Elderly people in need of care can be monitored to register falls and signal for help. With no needed maintenance, the device is very user-friendly.

The implemented sensor types are not limited to sensing force. Measuring temperature over a longer period of time is a further possible scenario for medical applications.

This autarkic sensor system can also be adapted to other fields of application. As a safety monitoring system, for example for firefighters, it can trigger an alarm if no data is transmitted, meaning that the person wearing the system is not moving. Such a device can be used to simplify access control. Doors can be unlocked if a person with right of access approaches or locked otherwise. For this application, an embedded system can be built into specialized safety shoes or into an insole that can be inserted in any shoe.

Another use case is a wearable fitness gadget that counts steps or tracks position. Energy harvesting simplifies the usage of such a gadget significantly, since it is independent from any limited battery lifetime.

Apart from exploiting a walking movement, the developed system is also suitable for other applications in which a mechanical motion is present. Harvesting energy can also be done from an industrial machine with moving parts, while the autarkic sensor monitors a process or machine in the production line.

6 CONCLUSIONS

The target of this project was to implement a sensor to monitor and support a healing process by measuring the applied weight on an injured lower limb.

Several other works in this field have been done previously. Comparable systems use batteries (Merrett et al., 2009) that need to be replaced or

charged. Introducing energy harvesting as a power supply increases the security of the system and makes it more user-friendly. Electrical energy is generated directly from the human motion and is available as needed.

The presented system is preferably implemented into foot or leg orthoses, prostheses, shoes or into crutches since the energy harvesting system relies on the vertical force from the weight of the wearer. The piezoelectric element produces a voltage when being deformed. With some adjustments, it is also possible to apply the sensor system on other body parts, such as the arms, provided a mechanical movement is present that can be used to bend the piezo buzzer.

A two-part system, where energy is harvested from the walking motion and a sensor is used to monitor another part of the body can also be taken into consideration. However, user-friendliness would be reduced by a device more complicated to apply.

The prototypic system has potential to be optimized in future work. This includes optimizing the harvester circuit in terms of efficiency and input voltage range. The used LTC3588 buck converter is limited to 20 Volts. Tests showed a significantly higher efficiency at higher voltages of up to 80 Volts. This potential should be exploited.

The possibility to stack the piezo elements is also worth analyzing. Two or more piezo buzzers can be used simultaneously to increase the power output at the cost of a larger device. Depending on the application and the required energy, it could be a viable solution.

An expansion of functionality is planned, particularly with respect to the used sensor types and construction form, to implement other applications.

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