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Battery-Free Classroom Response System Using Piezo-Electric Buttons

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Abstract: A completely energy autarkic design for a classroom response system is presented. Maloperation by the user is prevented with the chosen design (no unnecessary buttons and switches). Electronic classroom response systems have been around for quite a while and do exist in various forms and flavors. Most commercially available solutions, however, have several disadvantages. The new device is an easy-to-use, robust form of a clicker, which takes its energy from the click itself, due to a very low-power system using only an energy of around 15 µJ per wireless telegram transmitted from each student to the teacher's computer. The described system serves as both, a method to check students' progress in any field of lecturing as well as a tool that (by its development) instructs students in the field of "Energy Harvesting for Small Wireless Devices". The system also contributes to raising awareness of the material and energy balance in today's electronics.

Keywords: piezo, classroom response system, clicker system, low-power wireless system

1 Introduction

Long gone is the time when lecturing was considered as the act of reading from a book in class. Reminiscent of that time is the English academic expression "Reader". It does not necessarily have to be as extreme as Mazur (1997) more than 20 years ago, when he essentially demanded of the students to read his textbook before coming to class. He argues that it would be a waste of the students' time to have him repeat what is printed in the textbook. Even with a less extreme view, the activation of students in a class is important in order to keep them focused on the contents presented. Many places have reported successful application of classroom response systems, e. g. the physics faculty at the University of Colorado, Duncan (2006), identified an increase in class attendance from 60 %–70 % to 80 %–90 % after introducing the commercially available iClicker system (www.iclicker.com), thereby interactively involving students into the lecture. Classroom response systems allow the interactive solving process of multiple-choice questions. Bruff (2009) and many other authors offer a variety of forms of formative assessment by the help of classroom response systems. Several seminal papers such as by Fies and Marshall (2006); Martyn (2007); Caldwell (2007); Keough (2012), give a picture of the research in this field including best practices and further literature lists.

During an ongoing term, the lecturer often may only have little knowledge of the individual students' status in terms of comprehension. The idea behind the presented device is to involve students more in the lectures, while also providing feedback to the lecturer. One way of using such a system is to start every lecture with a short quiz revisiting the most important issues of the past lecture. It has been observed that both — the lecturer and the students — benefit from this use-case. On the one hand the students are motivated to reflect the past lecture and look up unclear points again. On the other hand the lecturer receives immediate feedback about how well the students have understood the topics studied so far. With this knowledge the lecturer is able to eliminate knowledge gaps before starting a new topic. This approach ensures that the acquisition of new knowledge, which might base on the last topic, is not endangered by any uncertainties on the students' side.

Commercial classroom response systems have been around for quite a while and do exist in various forms and flavours. They might be categorized into three groups according to what the students hold in their hands: Dedicated hardware solutions (clickers), software solutions (on a generic platform such as a smartphone), and technology-free solutions (at least with respect to the student). The last includes a showing of hands or holding up cards, which are evaluated by the teachers. Interestingly, at least one approach is known, plickers

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(www.plickers.com), where the cards contain a QR-code (two-dimensional bar code). These cards are held up by the students in one of four orientations, indicating their choice of answer and are then scanned by the teacher's smartphone.

Software solutions running on students' smartphones, tablets or even PCs are also in wide use, e. g. Kahoot! (www.kahoot.com) and can even be integrated in some larger systems such as Moodle or Twitter, see Kim et al. (2015). A specific design by a student is described in Murer (2011). However, such a systems has several disadvantages: The students' devices might not be compatible with the application, some WLAN infrastructure, with all participants contained, needs to be operable, the devices might be out of battery, or other push-message applications on the devices simply distract the students.

For the remainder of this paper the focus lies on the solutions with dedicated hardware. These systems have—in addition to considerable costs—often the following drawbacks:

1. Each device is powered by a battery, which has to be replaced after a certain period depending on the frequency of usage, the power consumption and the efficiency.
2. The devices need to be switched off after usage, otherwise battery life is further shortened.
3. The devices need to be properly configured in order to work within the assigned group.
4. The devices have more knobs and buttons to fiddle than necessary, leading to confused and distracted students.

2 Design Approaches

A proprietary classroom response system—named HSRvote—has been developed at the Institute for Communication Systems at the University of Applied Sciences Rapperswil. The aim of the project was to develop an easy-to-use response system, which does not exhibit the drawbacks listed above. Some key characteristics of the proprietary system design have been focused upon from the very beginning: low-power operation, no on/off switches, four buttons only to choose one of up to four given answers. The purposes behind these characteristics were that no configuration on the devices is needed, the buttons are self-explanatory and nobody should be punished for not switching off the device (in terms of battery lifetime). Figure 1 shows the HSRvote system, which consists of 30 handheld devices and a USB receiver.

Figure 1: Set of 30 classic HSRvote devices with a USB receiver.

Due to the fact that one device uses only as little energy as 100 μJ per button press and close to nothing when sleeping, the battery lifetime of the initial design was estimated to be 8-10 years. Of this small amount of energy less than 1 % is radiated, see Fleischmann and Mathis (2016a), using a short IEEE 802.15.4 one-way radio telegram shorter than a millisecond in duration. This comes as no surprise when working out Shannon's capacity, which indicates that the transmission of a bit of information over a distance of 100 m can be achieved with only a fraction of a pJ of energy, see Mathis (2016). The large part of the energy is used up by the microcontroller wake-up process. In order to minimize the energy consumption, the RF receiver inside a USB dongle on the teacher's PC does not transmit back. To extend battery life even further, no ARQ (automatic repeat request) scheme was implemented. However, successful reception of the users' vote is confirmed visually by animating the corresponding icon in the PC software.

Some additional features were later brought into play but were invisible to the user: A wireless feedback channel was described in Knutti, Tobler, and Mathis (2014) and an encrypted operation using ciphers in Loser and Amman (2014). Both approaches added functionality in terms of link availability and security, but compromised battery lifetime heavily.

All design variants mentioned so far have the same USB receiver to be connected to the teachers PC. Newer notebooks have few USB slots, hence methods were sought to get rid of an external receiver. A possible solution is brought in by IoT (Internet of Things) systems. A LoRaWAN approach was evaluated in Gujer and Mugioiu (2016), with the result that the energy consumption is raised by about a factor of 100 compared to the original design and the latency times are in the range of several seconds, which made the IoT approach unsuitable for the application. Since most PCs and tablets have built-in Bluetooth receivers, the use of transmitting the message via BLE (Bluetooth Low Energy) has been investigated as well in Kunz and Schläppi (2017). The latency times are much shorter than with the IoT approach. However, the BLE transmissions also use much more energy than the original proprietary design.

The question arises as to whether it is possible to have a low-power transmission running solely on the press of a button. Some commercial light switches use electromechanical energy but they are large in appearance. Piezoelectric transducers produce much less energy but are smaller in area and also very thin. It turned out that the 100 µJ used by the aforementioned design are exceeding the energy obtained by a single button press by a factor 5 to 10, reported by Wright and Suter (2014). A customized wireless protocol, also in the license-free 2.4 GHz ISM band, was therefore designed in order to further decrease the amount of energy needed.

3 Energy Harvesting

An additional area of interest in conjunction with wireless devices is energy harvesting. In this context, this refers to the ability to harvest the energy needed for transmission and as a consequence get rid of the battery. An early attempt resulted in a conference badge, which is equipped with a fixed coil and a moving magnet. By shaking the device, the induced voltage in the coil is used to charge a storage capacitor. This harvested energy is then used to put the device (with the original design) into operation with the same functionality, see in Knutti and Buchmann (2010).

A more straightforward approach to energy harvesting is of course the use of a small photovoltaic cell, which was tried by Kunz and Schläppi (2017). The scope of application is drastically limited in rooms where the light is dimmed, which is often the case in auditory halls.

4 Electronics Design

Piezo elements are known as acoustic transducers, e. g. used as beepers, where they convert electrical into mechanical energy. However, they can also be used to accomplish the opposite, i. e. by transforming mechanical oscillations into a constant flow of electrical energy. In this application, the piezoelectric transducer is not excited by acoustic waves but via mechanical deformation. Thereby, the peak-to-peak voltage produced during this deformation is generally large in magnitude (>60 V) while the available current is very low (a few µA), with a strong dependence on the strength of the button press. To ensure longevity, the circuit needs to be protected against voltage overshoots, see Orecchini et al. (2011).

To maximize the energy harvested, the following key concepts are employed in the *HSRvote battery-free* system (Figure 2): Firstly, since pressing and releasing

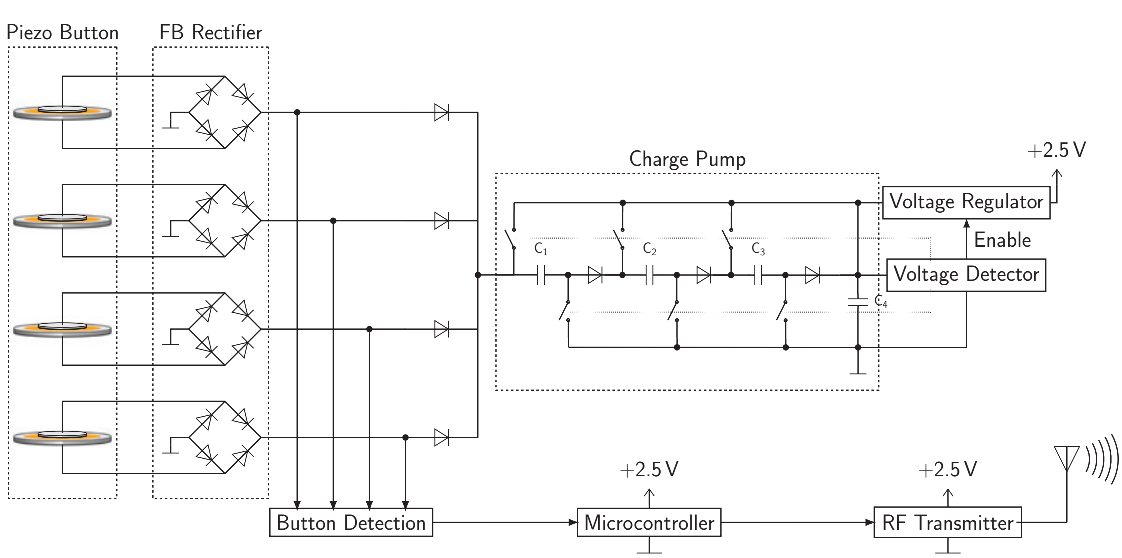

Figure 2: System overview HSRvote battery free.

the piezo-based button generates both a positive and a negative voltage peak, full-bridge (FB) rectifiers consisting of four diodes for each piezoelectric transducer are deployed. Secondly, a suitable storage capacitor is evaluated, which stores the charge generated by each button press and supplies it to the rest of the circuit. The energy transfer is maximized, if the external storage capacity matches the internal capacitance of the piezoelectric transducer, which is about 35 nF. However, using such a small storage capacitor leads to voltage levels which might damage the subsequent semiconductors. One challenge of choosing an optimal storage capacitor is therefore the compromise between being large enough to provide the required charge, yet small enough for a sufficiently high voltage. The solution to this problem is to utilize a so-called charge pump, in which four capacitors are charged in series and discharged in parallel. Thus the storage capacitor is realized as a series of four capacitors (C_1 to C_4). As soon as the voltage across C_4 has reached 6 V, the voltage detector closes all switches simultaneously, thereby changing the bank of capacitors from series- to parallel-connected. This way, the charge delivered by the piezoelectric transducer of around 2 µAs is converted into a usable charge of 4.6 µAs, while reducing the voltage from 24 V to 6 V.

Finally, the voltage at the output of the charge pump is converted into a stable 2.5 V supply voltage for the microcontroller and the RF transmitter. Since most voltage regulators guarantee stability only when connected to an output capacitor of a certain size (e. g. 100 nF), a so-called “capless” voltage regulator had to be evaluated. The microcontroller is a low-power MSP430 from Texas Instruments. The EM9203 from EM Microelectronic was selected as RF transmitter because of its very low power consumption during transmission and wake-up.

Every button press results in about 20 µJ of harvested energy. This is more than sufficient for transmitting a short wireless telegram of around 200 µs duration and a power of 2 mW, (resulting in a transmitted energy of 0.4 µJ). Most of the harvested energy is consumed during the start-up phase and by the transmitter during the transmission itself. The receiver is built up by the same two ICs; however, since it sits on a USB dongle, no energy harvesting is needed.

Given the output power of 3 dBm, the transmitting and receiving antenna characteristics and the transceiver performance, the available link budget can be estimated. This leads to a maximum transmission distance of several hundred meters in a so-called open field environment, see Fleischmann and Mathis (2016b). With potential obstacles, propagation conditions for indoor usage are more challenging. However, the results indicate that the available link budget presumably is sufficient even for use in a larger auditorium.

5 Wireless Protocol

In the previous versions of the HSRvote, the IEEE 802.15.4 wireless transmission protocol has been utilized to send the data to the receiver. However, no commercial protocol allows operation of transferring messages with as little as 20 µJ of energy; only a proprietary transmission wireless protocol is able to transmit data with this little amount of energy. The EM9203 utilizes such a protocol in the license-free 2.4 GHz to 2.4835 GHz ISM band, according to EM MICROELECTRONIC – MARIN SA (2014). The message structure sent after every button press is illustrated in Figure 3. It consists of the receiver’s address, several flags for packet identification, the payload, and a cyclic redundancy check for transmission-error detection. The payload contains the classroom set ID, the device ID and the number corresponding to the pressed button.

The use of a proprietary protocol and a small payload allow the transmission of a wireless telegram, which needs a total energy of less than 20 µJ.

6 Classroom Sets

Figure 4 depicts an HSRvote battery-free classroom set consisting of 30 transmitters and one USB receiver.

The piezoelectric transducers are mounted on top of the transmitter PCB as shown in Figure 5(a) using a special foil technology developed by Algra Industrial Technology. The enclosure for the transmitter was designed by (mechanical engineering) students in the shape of a green leaf to highlight the green technology inside. The front cover uses green plastic including softer material for the buttons, which are pressed by the user onto the piezo elements. The back cover is left transparent to show the PCB

Preamble	Address	Flags	Payload	CRC
1 byte	3 bytes	1 byte	5 bytes	2 bytes

Figure 3: Wireless packet format of the EM9203 transceiver.

Figure 4: Set of 30 HSRvote battery-free devices with a USB receiver.

and the absence of a battery. Both sides of the enclosure are shown in Figure 5(b) and Figure 5(c), respectively.

7 PC Software

A dedicated software has been developed for the HSRvote system. It allows the lecturer to create subject-specific questions using the integrated question editor. Figure 6 shows the software appearance. As soon as a student pushes a button for answering the question, the leaf icon with his/her device number appears on the screen. Thus, the student immediately receives feedback that his or her answer has been received. Until the adjustable countdown has expired, the student is allowed to change his/her answer by pressing a button again. As soon as the countdown has expired, the correct solution is presented to the students. If a certain student's answer was wrong, the corresponding numbered leaf changes color and floats to the bottom, animated as a leaf falling from a tree. Given the displayed result, the teacher can decide whether students have understood a topic or whether there is a need for clarification. The software allows the teacher to export each quiz result into a PDF or Excel file. The questions can also be exported and saved for further use.

8 Outreach

It is widely accepted that programs and activities are needed in order to get young people excited about engineering. Many institutions are pushing such STEM (science, technology, engineering, and mathematics) initiatives. Sometimes, in particular in German-based countries, they are also referred to as MINT (mathematics, information sciences, natural sciences, and technology) initiatives. The University of Applied Sciences in Rapperswil (HSR), Switzerland, has selected 50 high-schools that have each received a classroom set containing 30 classic devices (containing batteries) each in order to promote the idea of designing and producing hardware in Switzerland, see Knutti, Tobler, and Mathis (2014). Both for the classic as well as for the battery-less devices, the housing is manufactured at HSR by the Institute of Material Science and Plastics Processing. As a result, everything from embedded electronics, firmware, PC software to the mechanical design has been developed by engineers educated at HSR.

9 Lessons Learnt (Survey Results)

A survey carried out among 10 students of a small class has revealed some interesting facts. The survey itself has been implemented using a PC software in order to

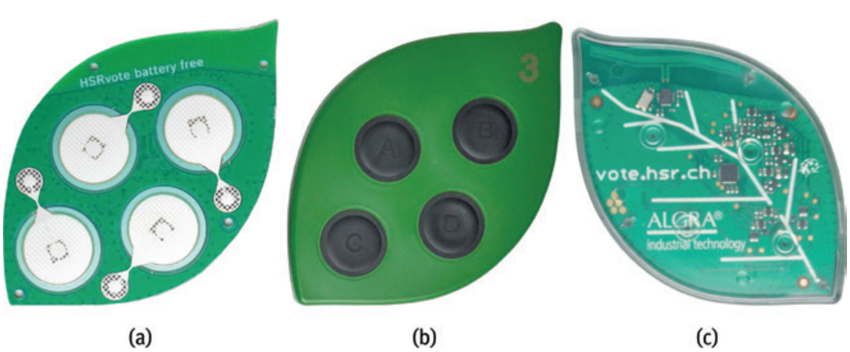

Figure 5: HSRvote battery-free device: (a) top side of PCB including piezos under the foil, (b) top side of cover, and (c) bottom side of cover containing electronic parts and a small folded-dipole antenna etched on the PCB at the very top.

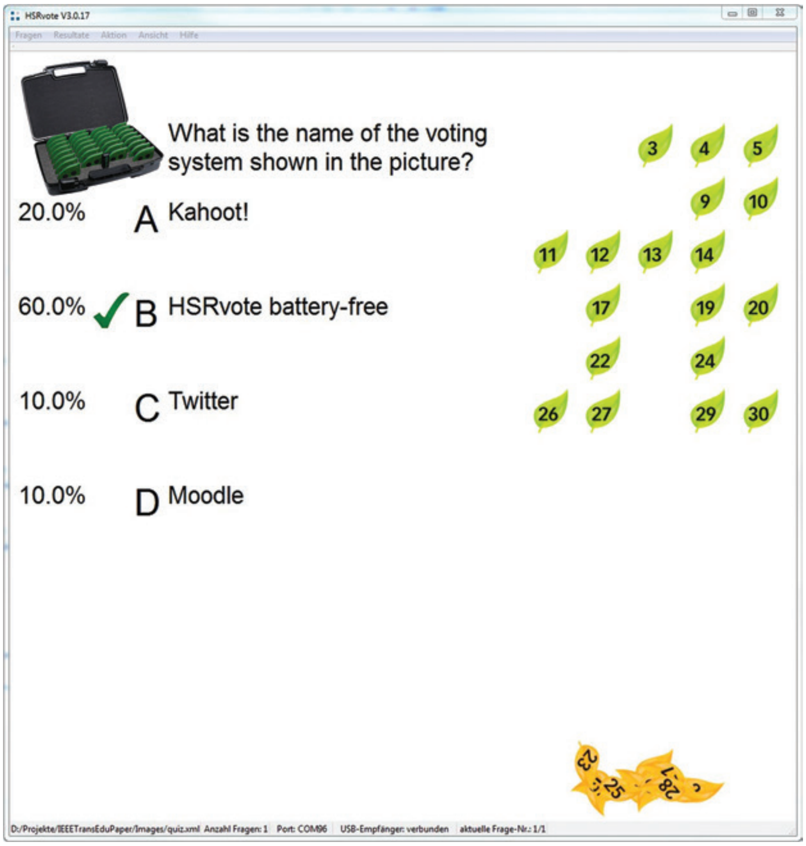

Figure 6: The appearance of the software after the countdown expired.

allow free-text answers. Two questions of the answer type "yes/no" were asked. The first one was: "Do you find the idea of asking questions at the beginning of the lesson using HSRvote appealing?" 10 out of 10 students answered with a "yes". The second question: "Has the quiz motivated you to prepare yourself better to the lecture?" was answered with "yes" by 5 out of 10 students. Finally, 6 out of 10 students used the opportunity to give a freely formulated comment. These statements were verbatim (translated into English):

- "HSRvote diversifies the lecture and motivates me to repeat the contents of the previous lecture."
- "Personally, I perceive the quiz as highly motivating. In addition, it introduces some action into the morning and wakes me up."
- "Superb idea! Great fun factor and motivates us students to prepare better to the lectures (high learning effect)."
- "Superb idea and implementation, fosters the repetition of the teaching material to a high degree."
- "It would be nice to have all questions (including solutions) at the end of the term in order to get prepared for the exam."
- "I find HSRvote a good start into the lecture. We repeat the stuff and in contrast to traditional oral questions addressed to the class, everyone produces their own thought on possible solutions."

10 Special Playing Variations

The following list contains variations to the simple multiple-choice question session that have been tried out at the University of Applied Sciences Rapperswil.

Delay the Answer Options After a question has been displayed, some time elapses before the students get the answer options, which might bias their opinions untimely. Delaying by a few seconds stimulates the students to think about any potential answer and therefore dive deeper into the topic.

Hand out Questions for Homework This is related to the variation given above. However the delay time is not a couple of seconds but a week or two. The lecturer might hand out the questions to think about for next week's lecture. The students can then work out solutions without being given the answer options.

Ask the Same Question Twice Regularly, the same question has been asked twice in a row. In the first attempt to answer the question, the students were not provided with the solution but with the percentage each answer has reached. The students were then given time to discuss (peer-instruction tuition). An interesting situation arises when the right-answer group is a minority, but has more convincing arguments. Prior to the second go, the students are asked to agree among each other on one choice, given the arguments they have just heard.

Read Questions and Answers Only Without Displaying Them As an exercise to train the memory, neither questions nor answers are displayed. The instructor reads them to the students by asking the question, followed by the answer options. The students have to develop a technique for memorizing this, similar to the ordering process in a restaurant without a written menu.

Coupling two Questions Sometimes it is an interesting start into a topic to place a right/wrong question first. The second question might then address some more background information by asking a why question, e. g. "Why do you think this is the case?"

5-min Assignment When calculations are involved, the students can be asked to work something out on a sheet of paper. After they get the result they press the right answer button. This way the lecturer knows when the students are ready for resuming class.

Check Reading Assignment When students were asked to study a literature text as an assignment, control questions can be asked in order to check their comprehension.

Make Students Write the Questions Another educational method is to let students write the questions. The syntax of the xml file is easily understood. Additionally, the software comes with a question editor, which increases the comfort of editing questions. The question text as well as the answer text might be supported by pictures in the file formats *.gif, *.jpg, and *.png.

Mid-Term Exam Whereas most of the usages mentioned are accounting for formative assessment, summative assessment in the form of mid-term exams are of course also possible.

Get Feedback on Lectures If the lecturer wants to get feedback on his/her lectures, he/she might ask questions on the speed, on the interests of the students, on homework load, and on many other issues. Naturally, there is no correct answer marked, so it is more a poll than a quiz.

11 Conclusions

An energy-harvesting classroom response system with many possibilities for polls and quizzes has been presented. The usage complexity on the user side has been reduced to the minimum, yet allowing a large flexibility on the teacher side. A simple press of a piezoelectric-transducer button delivers enough energy to initiate a wireless telegram to the teacher. Such systems have been distributed to high-school classes to encourage preuniversity students taking up careers in STEM, in particular electrical engineering. Furthermore, the system has been used as a platform to carry out research in different directions by investigating different aspects such as power consumption, secured transmission and wireless sensor systems in general.

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