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DIGITAL MEMS MICROPHONES FOR REMOTE MONITORING SYSTEM BASED ON SOUND ANALYSIS

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Sounds emitted by mechanisms and organisms contain information that can be used to diagnose the current state of an object and make predictions. There are known examples of the use of sound for diagnostics of pipelines, composite materials, industrial equipment. In most cases, devices with one sensor and limited functionality are used for this purpose, requiring a specialist to be in close proximity to the object under analysis. The system includes a set of digital microelectromechanical (MEMS) microphones, information from which is transmitted via Bluetooth to the mobile device. The system in a round-the-clock mode quickly registers changes in the spectrum of the sound signaland indicates possible malfunctions, damage to equipment and materials, etc. This allows preventing irreversible consequences. In this system, it is expedient to use digital MEMS microphones due to their low power consumption and low sensitivity to environmental influences, which is an important factor when deploying a remote monitoring system of industrial equipment.

Keywords: MEMS, digital microphone, piezoelectric microphone, capacitive microphone, Bluetooth, Bluetooth Low Energy, sound analysis.

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ЦИФРОВЫЕ МЭМС-МИКРОФОНЫ ДЛЯ СИСТЕМЫ ДИСТАНЦИОННОГО МОНИТОРИНГА НА ОСНОВЕ АНАЛИЗА ЗВУКА

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Звуки, издаваемые механизмами и организмами, содержат информацию, которую можно использовать для диагностики текущего состояния объекта и прогноза на будущее. Известны примеры использования звука для диагностики трубопроводов, композитных материалов, промышленного оборудования. В большинстве случаев для этой цели применяются устройства с одним датчиком и ограниченным функционалом, требующие нахождения специалиста в непосредственной близости к исследуемому объекту. Предлагается система для дистанционного мониторинга, включающая в себя набор датчиков-микрофонов, информация с которых передается посредством Bluetooth на мобильное устройство. Система в круглосуточном режиме оперативно регистрирует изменения в спектре звукового сигнала, свидетельствующие о возможных неисправностях, повреждении оборудования и материалов и т. д., что позволяет предупредить необратимые последствия. В данной системе целесообразно применять цифровые МЭМС-микрофоны вследствие их низкого энергопотребления и низкой чувствительности к воздействию окружающей среды, что является важным фактором при развертывании системы дистанционного мониторинга промышленного оборудования.

Ключевые слова: МЭМС, цифровой микрофон, пьезоэлектрический микрофон, ёмкостной микрофон, Bluetooth, Bluetooth Low Energy, анализ звука.

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Introduction

Microelectromechanical systems(MEMS) consist of both microelectronic and micromechanical components. MEMS devices are usually implemented on a silicon substrate. There are two basic types of such devices. Ohmic devices are controlled by electrostatically controlled cantilevers. Capacitive MEMS are developed using a moving plate or a sensing element, which changes the capacitance. There is a wide range of devices that can be implemented using MEMS. They are accelerometers, pressure sensors, thermoelectric generators [1], microphones [2], etc. Using MEMS versions of such devices allows decreasing the device size and power consumption. In some cases, it also leads to reduction in the influence of temperature, vibration and so on.

The important research field is design of high sensitivity digital MEMS microphones for various consumer and industrial electronic applications. They are automobiles, telephones, hearing aids, mobile phones, tablet PCs and personal audio systems [2]. Advantages of such microphones are small size, low cost and easy integration with CMOS circuits: the MEMS microphone and its signal processing integrated circuit can be monolithically integrated on a single chip [2]. Also, MEMS microphones have less sensitivity to temperature, vibrations, and mechanical shocks [3]. Therefore, it is preferable to use such type of microphones in remote monitoring systems that carry out surveillance on the object or environment state based on the sound analysis, especially, if such a system works in aharsh environment, for example, an industrial one.

The purpose of the review is to inform the reader with the MEMS microphonesoperation principles, the protocols used for data transmission, the Bluetooth Low Energy (BLE) specification and the architecture of the remote monitoring system based on sound analysis.

Types of MEMS microphones

A microphone is an acoustic-mechanical-electrical sensor that converts acoustical signal into electrical one that can be further processed. The analog electrical signal is converted into the digital form by the analog-to-digital converter (ADC) [4, 5]. Then the digital code from the ADC output is converted according to the protocol (I2S, SPI, etc.) used. After that by the given protocol the data is passed to the further digital devices for processing.

MEMS microphones are widely used in mobile applications such as smartphones, laptops, hearing aids, digital assistants, etc. due to their smaller sizes, higher signal to noise ratio and lower power consumption in comparison with traditional electret condenser microphones [6]. Also, as was said before, MEMS microphones have less sensitivity to the environment impacts. Thus, such kind of microphones can be used in remote monitoring systems for industrial applications.

Generally, three types of MEMS microphones are piezoelectric and capacitive [2, 7]. Capacitive MEMS microphones show high sensitivity and CMOS compatibility, while maintaining low power consumption [2] and remain the mainstream sensing technology for commercial products [7]. Such kind of microphones usually consists of a diaphragm, a back plate and an air gap. The principle is change in voltage by changing in capacitance. The diaphragm is vibrated due to acoustic pressure applied over it. This leads diaphragm and back plate behave as a capacitor [8]. Biased with a DC voltage, the capacitance change is converted into an electrical signal [2]. Capacitive MEMS microphones allow to improve miniaturization, integration and cost of the acoustic systems by leveraging the MEMS technology [2]. The performance of such kind of microphones can be increased by implementing the special design of the diaphragm and the back plate [7]. However, the structure of the capacitive sensing microphone is fragile to water vapor or dust [7]. This makes an additional water/dustproof packaging needed for such microphone when using in the harsh environment. The requirement of such special packaging leads to increasing the microphone cost. On the other hand, the piezoelectric sensing microphone could tolerate the influence of harsh environment [7] and has more robust mechanical structure with no air gap [9]. The piezoelectric sensing is performed by converting mechanical stress into electrical charge[10]. In such microphone the sensitivity is based on the properties of piezoelectric elements [11]. Piezoelectric MEMS microphones are extensively studied to improve acoustic performance [7]. Many approaches such as structure design, material usage, stress distribution, etc. have been proposed to improve performance of the piezoelectric microphone [7]. However, the enhancement of the piezoelectric film stress induced by the sound pressure and the air leakage from gaps between the diaphragm remain design concerns [7].

MEMS microphones can also be divided into two types: omnidirectional and unidirectional [6]. The omnidirectional microphonegenerates an electrical response from acoustic energy arriving from all directions around the device. Most of these microphones are capacitive ones [6]. The unidirectional microphone has its strongest output when acoustical energy arrives along a single axis vertical through or parallel with the surface of a vibrational membrane [6]. Both types of microphones can be used in a remote monitoring system for sound capturing. Omnidirectional microphones are applied when the system have to seize surrounding sounds, for example, from the nearby devices or equipment. Unidirectional microphones are used for surveillance over the specified equipment among others or over the specified part/location of the given equipment.

Communication protocols

After analog-to-digital conversion of the microphone output signal has been completed, the digital signal has to be formed from the ADC output bits according to the interface protocolused. This interface can be integrated with a MEMS microphone if CMOS-compatible technology is used.The high-speed protocol is needed for audio data transferring. There are several protocols or standards, such as SPI and I2S, that satisfy requirements for audio data transferring.

Serial Peripheral Interface (SPI) is a synchronous serial communication interface specification [12]. Devices can communicate over SPI in full duplex mode. The architecture with a single master and multiple slave devices is used.The master device generates the frame for reading and writing. Also, the master device selects a slave devicefor data transferring by activating the chip select signal on the latter. Slave devices not selected by the master do not participate in the data transferring. The SPI bus has four logic lines:

- SCLK or SCK – serial clock transferring from master to slave devices;
- MISO – Master In, Slave Out – data output from slave device;
- MOSI – Master Out, Slave In – data output from master device;
- SS or CS – Slave Select or Chip Select – this signal is set by the master device.

The SCLK clock signal generated by the master device sets the clock rate in the bus. Slave devices use this clock signal to determine when the data bits in the bus change.

Data transferring is carried out in packets. Usually, the packet length is 1 byte (8 bits). However, SPI implementations with various packet length are known. The master device initiates data transferring by setting the SS pin of the slave device to be connected to logic low. Data are transferred from the master to slave over the MOSI line and from the slave to master over the MISO line. After each data packet transfer the master device can set the SS line to the logic high for synchronization.

Inter-IC Sound (I2S) is a serial interface standard used for connecting digital audio devices [13]. The I2S bus has three lines:

- SCK or BCLK – continuous serial clock or bit clock;
- WS – word select or word clock line;
- SD – serial data.

The master device generates both SCK and WS clock signals. Slave devices will usually derive its internal clock signal from the external clock input.

Since the transmitter and receiver have the same clock signal for data transferring, the transmitter as the master has to generate the SCK signal, WS signal and data. In complex systems, there may be several transmitters and receivers, which makes it difficult to determine the master. In such systems, there is usually a system master controlling digital audio data-flow between the various devices. In this case, transmitters have to generate data under the control of an external clock, and thus act as a slave device [13].

Some digital MEMS microphones support only the pulse-density modulated (PDM) output [14, 15]. To communicate with these microphones SPI and I2S interfaces can be used. Usually, a PDM microphone has three lines:

- LR – left/right channel selection (input pin);
- CLK – input synchronization clock signal;
- DOUT – left/right PDM data output.

The LR pin is used to seize the stereo signal from two microphones. This pin can be connected to Vdd or GND bus to operate in the mono mode.

The PDM data can be further received and processed by the microcontroller unitusing its available interfaces, such as SPI, I2S or SAI (Serial Audio Interface) [14]. Then, this data can be transferred via wired or wireless (Wi-Fi, Bluetooth, etc.) communication channel.

Bluetooth Low Energy

Bluetooth Low Energy (BLE, also known as Bluetooth Smart) started as part of the Bluetooth 4.0 Core Specification [16]. Both Bluetooth Classic and Bluetooth Low Energy operate in the 2400–2483.5 MHz frequency range within the ISM 2.4 GHz frequency band. The data exchange in Bluetooth Classic happens over one of the 79 designated channels, while in Bluetooth Low Energy the number of designated channels is 40 [17]. The BLE power consumption is from 0.01 to 0.5 W and 1 W for Bluetooth Classic. The physical data rate of Bluetooth Low Energy is 1 Mbit/s, while for Bluetooth Classic this parameter can be up to three times greater reaching 1–3 Mbit/s. However, the latency of BLE is at least 10 times smaller in comparison with a classic Bluetooth, and is 6 ms and 100 ms respectively. The theoretical Bluetooth Low Energy working range is more than 100 meters. The minimum total time required to send data in BLE is 33 times less than that in Bluetooth Classic amounting to 3 ms and 100 ms respectively. Point-to-point and star network topologies are usually used in Bluetooth Low Energy, while piconet, scatternet and point-to-point topologies can be deployed in Bluetooth Classic [17]. A device in a BLE network can be a server or a client. The server is a peripheral device that transmits data from sensors or receives commands to manage devices connected to BLE module or transmits data to these devices. The client is a device that receives data from sensors or sends commands to manage devices connected to BLE module. Bluetooth Low Energy is commonly used for interacting with a wide set of sensors due to its low power consumption. However, there is no standard way of transmitting voice over BLE, consequentlya custom profile must be used [18].

System architecture

The architecture of the remote monitoring system based on sound analysis is presented in Fig. 1. It can be used for diagnostics of expensive industrial equipment and unique laboratory and research facilities. The system includes a set of digital MEMS microphones, information from which is transmitted

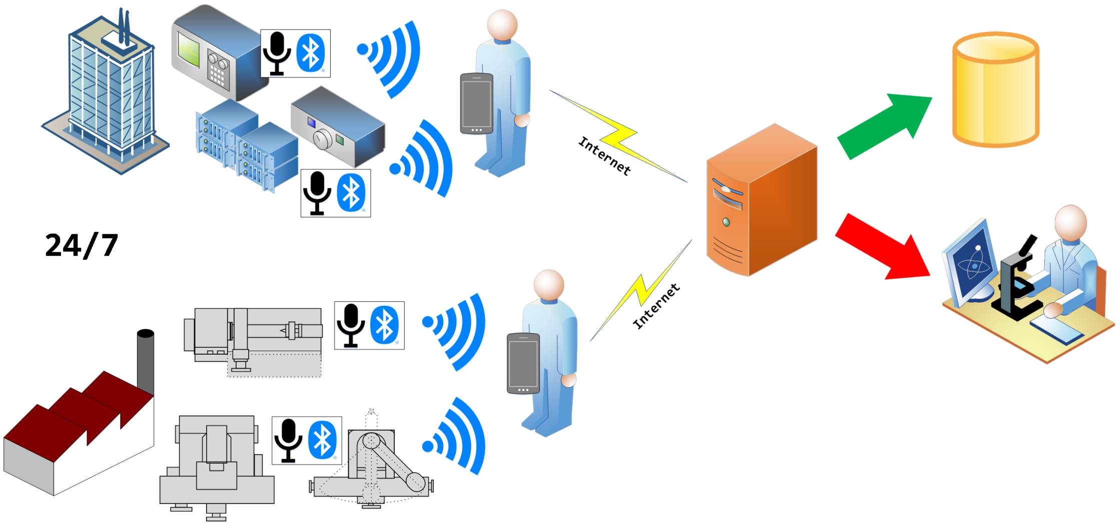

Fig. 1. Remote monitoring system based on sound analysis

via Bluetooth Classic or Bluetooth Low Energy to the mobile device. The microphones could be omnidirectional or unidirectional depending on the equipment being monitored. The use of Bluetooth allows reducing power consumption of sensors and, as a consequence, increasingthe battery life.

The received information is pre-processed by the mobile device and, if necessary, can be transmitted for additional analysis by a specialist using a personal computer. The system in the round-the-clock mode promptly registers changes in the spectrum of the sound signal, which indicate possible malfunctions, damage of equipment or materials, the presence of anomalies in the state of human internal organs, which allows preventing irreversible consequences. The system can be expanded to handle non-acoustic parameters of objects or the environment, such as temperature, humidity, dust, pressure, etc. This will allow obtaining a larger amount of data on the state of the facility and/or the environment for more comprehensive and detailed monitoring, as well as controlling parameters that are important for maintaining the operability of a particular facility.

Conclusion

The architecture of the remote monitoring system has been proposed based on sound analysis, which controls acoustic parameters of an object or an environment using sensors based on MEMS microphones. The future work is to create a prototype of this system using digital MEMS microphones, data from which are transmitted in the real time to a mobile device via Bluetooth Low Energy. A mobile application for preliminary intellectual processing of data received from microphones is going to be developed. Analysis of audio signals received from microphones for the presence of anomalies can be performed by using machine learning methods, for example, a neural network with an appropriate architecture.

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