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An intelligent barrier using ultrasonic technology

Přemysl Janů*, Barbora Odvárková[1]

The article is devoted to the complete design of an intelligent barrier that uses piezoelectric ceramic transducers as transmitter of an acoustic signal and as a receiver. There is a relatively rich device base on the market for these transducers. These transducers are also not economically demanding. The barrier is composed of three identical bars. A continues wave rectangular signal generation is used for excitation of the converters on the transmitting side. The receiving side is more complex. A signal from the receiving transducer is first analog pre-processed and converted to logical values of 0 or 1. Subsequently, these signals are processed in a microcontroller system, evaluated and a possible alarm of a presence of an intruder is signaled using a display, a light-emitting diode and a piezoelectric siren. The display also shows the number of alarms. Some intelligence is added to the system by classifying a potential intruder. The functionality of the system is verified in a detail and discussed.

Keywords: piezoelectric ceramic transducer, barrier, ultrasound, signal processing, Arduino, electronic security system, intruder, simulation

1 Introduction

Nowadays, greater demands are still placed on the protection of possession and people. Barrier detectors are mainly used in casing or perimeter protection systems. These systems are used to detect intruders (unwanted persons or animals) through any permeation into the building or the perimeter of the building (doors, windows, gates or other free permeation). Infrared and laser bars, barriers or curtains are mainly used for these purposes. Microwave barriers are also used. Technology using infrared radiation requires precise coaxial adjustment of the transmitter and receiver, as well as laser bars. The detection speed is not very high. Very fast movements are very difficult to detect. Microwave technology does not require such precise coaxial alignment of transmitter and receiver. The speed of detection is higher due to the wider detection characteristic of the system [1, 2]. These systems, especially for usage outdoor, are very expensive, so there was a reason to verify the functionality of ultrasound technology for this application, and therefore produce an ultrasonic barrier. Ultrasonic technology is used for very similar purposes, for example in industry as an ultrasonic bar, when it detects the presence of given goods on the belt. Such implementation of ultrasonic technology has not yet been used in electronic security systems [1, 2] and this article is devoted to the purpose. The article is devoted to the complete design of an intelligent barrier that uses piezoelectric ceramic transducers, which can be very easily obtained on the market of electronic devices and are not economically demanding.

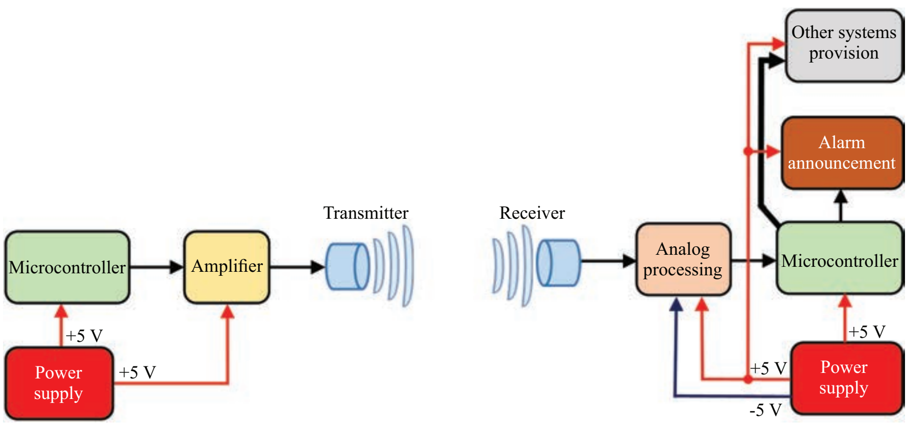

Fig. 1. Block diagram of the ultrasonic bar

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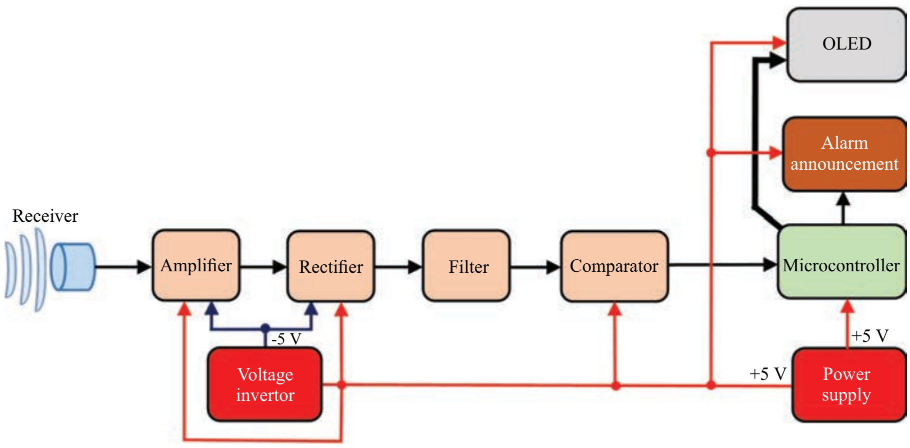

Fig. 2. Detailed block scheme of the receiving part

2 Design of the ultrasonic bar

Before designing of the intelligent barrier, specific implementation of the future system was first determined. Application to doors with a standard size of 0.8 m was assumed. The door could be located inside the building, or it could be outside door. Hence, the range of temperatures in which the system will work follows. In climatic conditions of the Central Europe, it is temperature ranging from -15 °C up to 40 °C. It is also possible to consider average year-round relative air humidity, which is 77% [3] and the atmospheric pressure close to the normal pressure according to the international standard atmosphere, thus at low altitude [4].

First, an ultrasonic bar was designed. The complete barrier then consisted of the individual bars. The block diagram of the design of this bar is shown in Fig. 1.

Significant parts of the ultrasonic bar are therefore piezoelectric ceramic transducers that function as transmitter and receiver. Piezoelectric ceramic transducer - transmitter converts electrical energy into acoustic energy. The acoustic wave then propagates through the environment, in this case in the air. Piezoelectric ceramic transducer - receiver converts acoustic energy back into electrical energy [5]. In this application, piezoelectric ceramic transducers commonly available on the electrical component market in air-to-air formation were used. The application of piezoelectric ceramic transducers operating with resonant frequency of 40 kHz was envisaged. There are listed converters that work with a higher resonance frequency, but here there is a greater attenuation in the environment [6], so these were used. For the excitation of the piezoelectric ceramic transducer - transmitter, a signal generated by a single-chip microprocessor was assumed, thus rectangular with the desired frequency and peak value (amplitude) of 5 V, which can be further amplified as needed. The signal is not modulated in any way. It is with a continuous wave. According to the very initial orientation testing, where the piezoelectric ceramic transducers were 2 m apart, it was found that the amplifier could be discarded. The signal level at the output of the piezoelectric ceramic transducer - receiver had the necessary level for further processing. Its value was 36 mV. The amplifier was no longer included in the final version. An Arduino Pro Micro [7] kit with a single-chip ATmega32u4 microprocessor [8] was used as the microprocessor system of the transmitter. It is one of the smallest Arduino kits. The transmitting part therefore reaches very small dimensions. Since in ultrasonic transducers, whose piezoelectric oscillating element is ceramic, there is a change in the resonance frequency with temperature [9], therefore it was assumed that the frequency change was programmed in a single-chip microprocessor. The power supply for the single-chip microprocessor and the amplifier should be +5V. The TSR 1 - 2450 DC/DC converter from Traco Power Company was chosen as the power supply system. It is possible to connect a DC voltage in the range of $6.5 - 36$ V to this converter. It is then possible to obtain stable voltage of 5 V with current carrying capacity of up to 1 A at the output [10].

On the receiver side, it was first necessary to perform analog preprocessing of a signal. Analog preprocessing of the signal consisted of amplifying the signal to the required level, rectification, performing filtering and comparison with a certain threshold value, thus converting it to a logic level 0 or 1. The logic level converted in this way is connected to a single-chip microprocessor. A single-chip microprocessor processes this information, evaluates it and ensures an announcement of an alarm, or provides the given information to other systems. The receiving part is supplied with the voltage of +5V and -5V for analog signal preprocessing. The receiving part is therefore significantly more complicated than the transmitting part. More detailed block diagram of the receiving part is shown in Fig. 2.

The amplifier was created by cascading two inverting operational amplifiers TL072C [11], whose voltage gain could be adjusted as needed using potentiometers. Furthermore, a two-way operational rectifier was used again with help of two TL072C operational amplifiers and BA159 rectifier diodes [12]. This was followed by a passive filter of low-pass type, which consisted of a ceramic

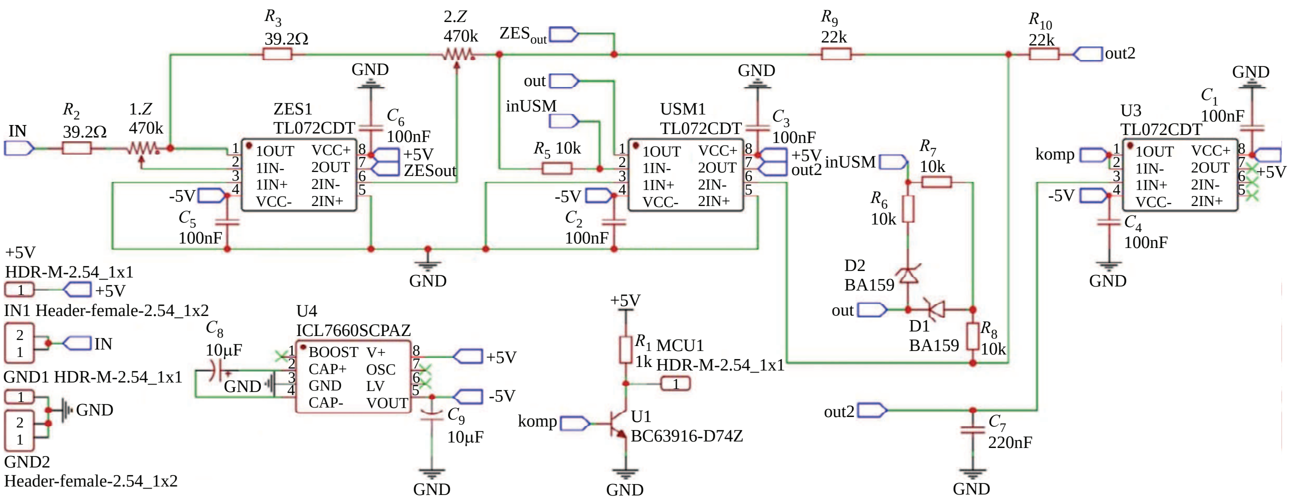

Fig. 3. Detailed electro technical scheme of final part of the analog signal preprocessing

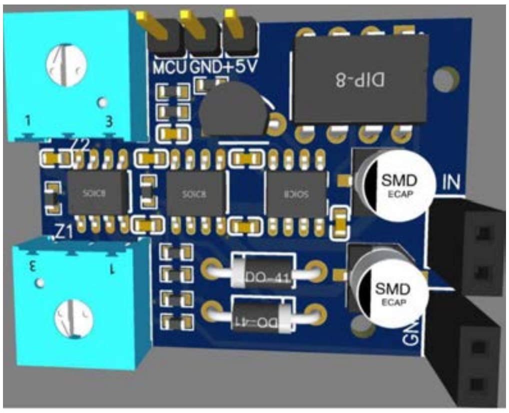

Fig. 4. Printed circuits board in 3d simulation(left)and realistically equipped(right)

capacitor of 220 nF. The last part of the analog signal preprocessing chain was a comparator consisting of BC635 transistor [13] with connection of combined emitter. The threshold value was equal to the magnitude of PN junction voltage. This value for this transistor is 0.5 V [13]. At the output of the transistor, the value is logical 1 if there is an obstacle between the piezoelectric ceramic transducers and logical 0 when there is no obstacle between them. In case of logic 1, an alarm should be generated.

The output of the transistor is conducted to the digital terminal of the processor system, which must be set as an input. The functionality of individual analog preprocessing components was verified in detail in the Micro-Cap 12 simulation development environment. Based on the correct function from the simulation results, a printed circuit board was designed in the Easy EDA design environment. The final electro technical scheme of the analog signal preprocessing is in Fig. 3. The given diagram is without the piezoelectric ceramic transducer, without the microprocessor system and without its accessories.

Printed circuit board of analog signal preprocessing in 3D simulation and realistically equipped with components is shown in Fig. 4. To miniaturize the printed circuit board, mainly components for surface mounting were chosen here.

The Arduino Pro Micro kit with single-chip ATmega32uF4 microprocessor was once again used as the processor system. Since the operational amplifiers in the analog part need to be powered symmetrically, it was also necessary to equip the receiving part with a power supply voltage invertor and thus create a complete symmetrical power supply. This represents the ICL7660SCPAZ from RENESAS Company integrated circuit [14] combined with two electrolytic capacitors of $10\,\mu$F. The power supply as such is again solved here by the TSR 1-2450

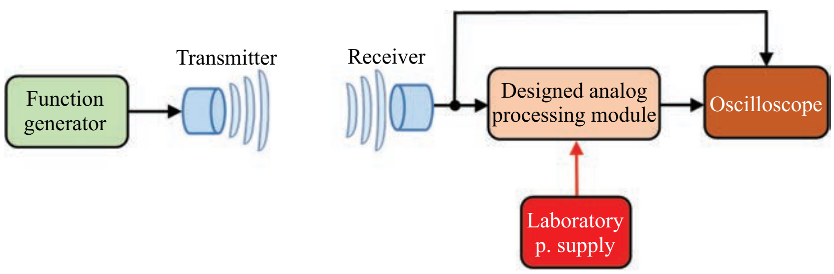

Fig. 5. Block diagram of the testing workplace

Table 1. Frequency range of specific transducers found during testing for temperature of 20 °C

Receiver	Transmitter		
	MCUSD16A40S12RO	MCUSD16P40B12RO	MA40S4S
MCUSD16A40S12RO	(39.6 40.9) kHz	(39.7 40.7) kHz	(39.0 42.2) kHz
MCUSD16P40B12RO		(39.6 40.5) kHz	
MA40S4R	(38.8 42.0) kHz		(40.7 41.6) kHz

DC/DC converter from Traco Power Company. A piezoelectric siren and LED are implemented for alarm signaling. To display a type and number of alarms, an OLED depiction unit with resolution of 128×32 points with an SSD1306 driver [15] is used. Communication with this display unit is enabled by the I2C data bus.

3 Testing of the ultrasonic bar

OWON AG 2052F function generator [16] was used for excitation signal of the piezoelectric ceramic transducer - transmitter. On this generator, a rectangular signal with peak value of 5 V and frequency defined by the technical documentation of the transducers, namely 40 kHz, was initially set, which was then modified. Piezoelectric ceramic transducer - transmitter and receiver were 1 m apart, thus with certain margin than the assumed distance of 0.8 m. The transducers were placed in the axis. The designed final analog signal preprocessing module was connected to the piezoelectric transducer-receiver. The output from this module was connected to the two-channel oscilloscope OWON XDS3102 [17], on which the necessary waveforms were displayed. The second waveform was the output from the piezoelectric ceramic transducer - receiver. The designed analog preprocessing module was powered by MATRIX MPS-3003L-3 laboratory power supply [18].

Four available converters were tested. Some of them were designed by the manufacturer to function as both transmitter and receiver. These were transducers with the designation of MCUSD16A40S12RO [19], and MCUSD16 P40B12RO [20] from the Multicomp Company. Furthermore, the transducers were designed primarily for the function of either a transmitter or a receiver. They were transducers marked MA40S4R [21] (receiver) and MA40S4S [22] (transmitter) by Murata Company. An example of the functionality of the system is shown in Fig. 6. The left part of the picture represents the case when the obstacle was not present and the right part of the picture the case when the obstacle was present. The yellow waveform presents the output from the piezoelectric transducer - receiver and the blue waveform the output from the transistor comparator. In case that there is no obstacle between the transducers, a harmonic signal appears at the output of the receiver with a frequency that is set on the function generator and an amplitude proportional to the attenuation in environment and the arrangement of the transducers. At the output of the comparator, it is value close to logical 0. In case that there is an obstacle between the transducers, an almost zero value will appear at the output of the transducer, and at the output of the transistor comparator a value close to the supply voltage of 5 V.

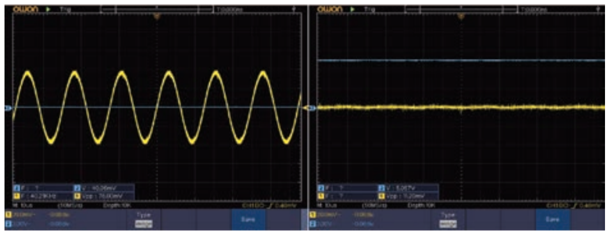

Fig. 6. Outputs from oscilloscope

Six measurements were performed with the mentioned converters. The mutual combination of pairs of these converters and the most suitable frequency for the given system is formed by Tab. 1. This table represents the temperature condition of 20 °C. The system showed correct functionality in all measurements, even in the case of significant misalignment of both converters from each other. In the case of outdoor temperature of $-2°$, it also showed correct functionality, but the limit values of the most suitable frequency ranges increased by 1 kHz. From this, it was concluded that significant regulation of the excitation frequency for the converters will not be needed. This testing also revealed that the most suitable pair of converters would be MA40S4S as transmitter and MCUSD16A(P)40S(B)12RO as receiver with the frequency set to 41.3 kHz, which was also used in the final implementation.

4 Final assembly of the ultrasonic barrier

Based on thorough testing of individual bars and selection of suitable piezoelectric ceramic transducers, complete ultrasonic barrier could be assembled. The barrier consisted of three identical bars that were attached to the frame of a standard door up to a height of 0.3, 1 and 1.6 m. The heights of the individual bars were chosen according to the practical situation, when, for example, just height of 0.3 m from the ground was chosen for the passage of an animal or a crawling person, the passage of a child or a larger animal corresponds to height of 1 m,

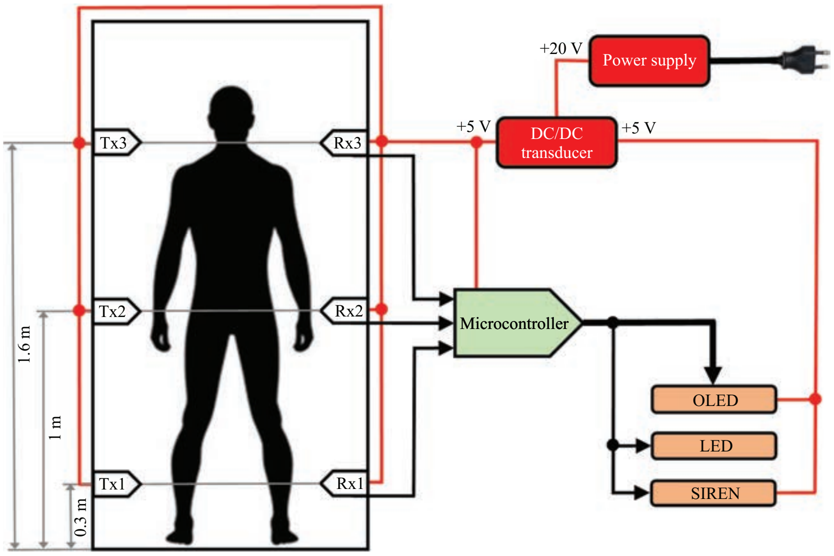

Fig. 7. Situational drawing of the assembled ultrasonic barrier

Table 2. Possible states on the individual comparators and their evaluation

Bit	Decimal value	Transmitter detection	Evaluation, alarm signalling
000	0	None	Peace – no intruder
001	1	Rx1	Animal, crawling man
010	2	Rx2	Not considered
011	3	Rx2 a Rx1	Child, larger animal
100	4	Rx3	Not considered
101	5	Rx3 a Rx1	Not considered
110	6	Rx3 a Rx2	Not considered
111	7	Rx3, Rx2 a Rx1	Human

and for an adult, height of 1.6 m was considered. Figure 7 presents the situational drawing.

The transmitter modules Tx1, Tx2 and Tx3 are made up of the kit with Arduino Pro Micro and piezoelectric ceramic transducer labeled MA40S4S without an amplifier. The receiving modules are made up of piezoelectric ceramic transducer with the designation of MCUSD16A40S12RO and the designed final version of analog signal preprocessing component. The outputs from the transistor comparators of these modules lead to the digital pins of the Arduino Pro Micro microprocessor system, which are set as inputs. Microprocessor system processes the values of the connected signals and provides visual and audio signaling of the possible presence of an intruder. The entire system is powered by adapter from distribution electrical network that allows the output voltage 20 V and maximum load current of 3.25 A.

After assembling the complete ultrasonic barrier system, it was necessary to program individual single-chip microprocessors both for generating the relevant signals and for evaluating the presence of an intruder. Part of the evaluation was also determination of possible nature of an intruder, and therefore equipment of a certain intelligence to the system. The codes for the applied microprocessor systems and their programming itself were carried out in the Arduino IDE development environment. The function tone (Output pin, Frequency, Time) was used to generate the relevant excitation signals for the piezoelectric ceramic transducers - transmitters. The arguments of this function are: defining of the output pin of the processor, the frequency of the signal and the time for which the signal is generated. In this case, a continuous wave signal is used, so this argument was not specified. One microcontroller was used for each transmitter, so in this application three. On the receiving side, one microcontroller was used to evaluate the states of individual transistor comparators. An overview of possible states and their evaluation is represented by Tab. 2.

From the given table it follows that the detection by the receiver Rx1 represents the least significant bit and the detection by the receiver Rx3 represents the most significant bit. The algorithm in the microprocessor system continuously tested the states of the individual inputs and assigned to them the appropriate decimal value. In the processor algorithm, the condition for multiple branching was just the decimal value. Decimal values 0, 1, 3 and 7 were considered, which were realistically usable. Other values were highly improbable and were therefore not considered. Peace was signaled at these values. The alarm was signaled by the system using a LED, a siren, and necessary message was displayed on the OLED. The algorithm in the single-chip processor also registered the number of considered alarms and displayed this on the OLED.

5 Function verification of the intelligent ultrasonic barrier

After the development, debugging and programming of the individual processor systems, it was possible to proceed to the final testing of the intelligent ultrasonic barrier. The system was tested by an adult passage. Both slow and fast passage were tested. During the slow passage, it was very clear to see how the individual bars in the barrier gradually detected the person. During fast movement, detection by individual bars could not be clearly seen, however, the system signalled alarm correctly. This resulted in the system is being able to detect both a fast-moving person and an animal and announce an alarm in case of intruder penetration into the guarded area. The real situation during testing is represented by the photo in Fig. 8. On the left side of the photo is possible to see the installation of the prototype of the intelligent ultrasonic barrier and woman who played the role of a figurine during the testing. On the right side of the photo is possible to see LED as visual alarm signal and OLED with the corresponding message and depiction of the number of given alarms.

6 Conclusion

The article presented detailed design of the intelligent ultrasonic barrier and verification of its correct functionality. The intelligent ultrasonic barrier uses piezoelectric ceramic transducers in an air-to-air configuration. They are not specialized devices, so they are very easily available on the market and relatively inexpensive. The ultrasonic barrier has a modern processor system implemented, but also very easily available on the market. The electronic devices in the module for analog signal preprocessing were again chosen so that they are very easily available and mostly in surface mount technology for miniaturization of the module. After thorough testing, the system appeared to be working properly. The barrier was able to detect even the fast movement of an intruder and signal an alarm. A simple comparison with the VAR-TEC DWB 2-57 two-beam infrared barrier was also performed. The proposed ultrasonic barrier appeared to be significantly better at detecting fast intruder movements. It detected fast movement without problems, and the tested infrared barrier had problems with detection. The proposed ultrasonic barrier was not compared with a microwave or a laser barrier.

The designed ultrasonic barrier represents a prototype that can be significantly modified in the future. As a first modification, only piezoelectric ceramic transducers can be built into a frame of an appropriate door, and the device for generating and signal processing can be installed outside the door frame. Another modification could be to generate a signal from only one processor. Here, it would be necessary to implement a simple transistor amplifier to enable the processor to drive more piezoelectric ceramic transducers. This is also related to the use of a certain modulation of excitation signal for possible incretion of detection sensitivity. However, the transmitting part would be more complicated. It would also be necessary to design a harmonic signal generator. In this case, it would be possible to produce a three-channel module for analog pre-processing of the signal from the transducers in receiving part and place it outside the door frame. In addition, for future work on this device, it is possible to equip the receiving part with a microprocessor system that enables wireless communication via Bluetooth, Bluetooth low energy, or Wi-Fi to transmit information about intrusions to other systems. Another option for wireless transmission is to equip the receiving part with a GSM module for transmitting short messages about object intrusion to the appropriate telephone number in the network.

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Barbora Odvárková was born in 1998 in Mladá Boleslav. She received MSc degree in Radar Technology and Electronic Warfare in 2022 from the University of Defence in Brno, Czech Republic. She is currently commander of group of soldiers at 532-nd Electronic Warfare Battalion, Opava, Czech Army Ground Forces. Her research interests include radar technology, electronic warfare, electronic security systems, sensors and sensors signal processing.