Chapter 16
The Using of Deep Neural Networks and Acoustic Waves Modulated by Triangular Waveform for Extinguishing Fires

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Abstract Current article introduces a new approach for detection of fires based on deep neural network (DNN) and their extinguishing using an acoustic fire extinguisher. Finding fires on video stream is based on low-cost hardware platform containing Movidius stick for hardware acceleration of the DNN used for fire detection. For this purpose, the fire extinguisher uses a sinusoidal acoustic wave modulated by a triangular waveform. The special design of the extinguisher guarantees that the sound pressure level will be sufficient for successful extinguishing of the fire in distance up to 130 cm.

16.1 Introduction

Nowadays, the traditional fire extinguishing methods are based on the effect of gaseous, liquid, or solid extinguishing agents on the selected flames area. The acoustic method turns out to be a good solution, among others, for fighting fires of spilled liquids. Its action is based on the dispersion of fire over a large area with the use of acoustic waves. This results in a gradual reduction of the flames, which are located on a larger area. However, in order to use this method effectively, it is

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necessary to emit acoustic waves at appropriate frequencies. The first documented attempts to extinguish flames with the use of acoustic waves were made in Poland (in 90 s) in the last century [1, 2], as well as in the last years in the USA (especially since 10 years ago) [3–9]. Further research has been carried out in Poland since 2017, which resulted in, among others, applications to the Patent Office [10–14]. Similar researches have become the subject of scientific efforts in agency Defense Advanced Research Projects Agency (DARPA), which in 2008 launched the Instant Fire Suppression Program (IFS program) aimed at searching for effective firefighting methods [3]. In the video presented by DARPA, it can be seen that the flames placed in the acoustic field (generated by two loudspeakers positioned on both sides of the fuel tank) were quickly extinguished. We are therefore dealing with two dynamics. First, the acoustic field increases the air velocity. As air velocity increases, the flame boundary layer of the combustion flame appears, facilitating the process of flame surface disturbance. Secondly, disturbing the flame surface leads to higher evaporation of the fuel, which expands the flame, but also reduces the total flame temperature. The combustion process will be disrupted by the distribution of heat over a larger area. Consequently, it is possible not only to significantly reduce the flames, but also to extinguish them completely. Similarly, a fire extinguisher designed by American students Seth Robertson and Viet Tran is suitable for extinguishing flames [4]. The device developed after a year of experimenting is equipped with an amplifier, a power supply, and a tube from which acoustic waves are emitted. The process of extinguishing with acoustic waves assumed that oxygen is the main fuel of fire. In turn the acoustic waves of appropriate frequency are able to push oxygen further out of the air. Still another solution presented in the "Myth Busters" program which proves that it is possible to extinguish a fire with the amplified, modulated human voice (with the use of computer techniques) [5]. Because the acoustic amplification limit reached by the firefighters exceeds the pain threshold of the human ear (due to excessive sound pressure), this solution is dangerous for human health.

Acoustic flames extinguishers using high and very high-power loudspeakers can be effectively supported by an innovative fire detection method using deep neural networks, based on learning from the images or video streams [16–23]. Dedicated sets can be used for image recognition [24, 25]. In order to replace traditional fire protection methods by the new technologies, numerous studies are needed, including the modulated acoustic waves produced by acoustic extinguishers. The benefit of the use of the acoustic waves is non-invasive character of operation (significant reduction of the equipment damage placed in the fire zone, thus reducing the costs and time needed for repairs), no need to give pressure tests of the tank with extinguishing agent and unlimited time of use in relation to traditional extinguishing methods. This time is limited with only by power supply delivered to extinguisher, electronics, and many others. For this reason, it is also important to understand the operation of conventional fire protection methods [26–28], the new developments in signal processing [29, 30], as well as the use of the Internet possibilities and electronics in practice. However, more effective extinguishing requires further research in the direction of the impact of low frequency and high-power acoustic waves on human health. Knowledge of the practical extinguishing properties of simultaneously operation of several acoustic extinguishers (or acoustic extinguishers composed of a set of sound sources in the form of subwoofers) is also needed.

16.2 Structure of the Acoustic Fire Extinguisher

In the scientific literature, there are known researches concerning the possibility of using acoustic waves of very low power to extinguish flames in a short distance from the output of the device. This distance was only a few centimeters from the extinguisher output. During these tests, electrical power supplied to the loudspeaker was very low (up to 20 W). The authors noticed that in order to find out how to use the technology of extinguishing flames by means of acoustic waves, it is necessary to conduct research on acoustic extinguisher with much higher power. The use of high and very high acoustic power makes it possible to increase the distance between the flame sources and the extinguisher output. The paper is a response to this call, allowing to determine the effect of acoustic waves on the extinguishing process at a much longer distance from the fire extinguisher output. It was unexpectedly noticed that the modulation of the extinguishing wave frequency has a positive effect on extinguishing process (scientific novelty). In addition, it has been noted that better concentration of the acoustic stream has a positive effect on the range and effectiveness of extinguishing effects, especially in the case of small areas. The research clearly confirmed the extinguishing effect of the acoustic waves.

The elements of the measuring station are: Rigol DG4102 generator with AM modulator; Proel HPX2800 power amplifier; SVAN 979 sound level meter with instrumentation and analog meters for measuring electrical quantities. The construction of the acoustic extinguisher is shown in Fig. 16.1.

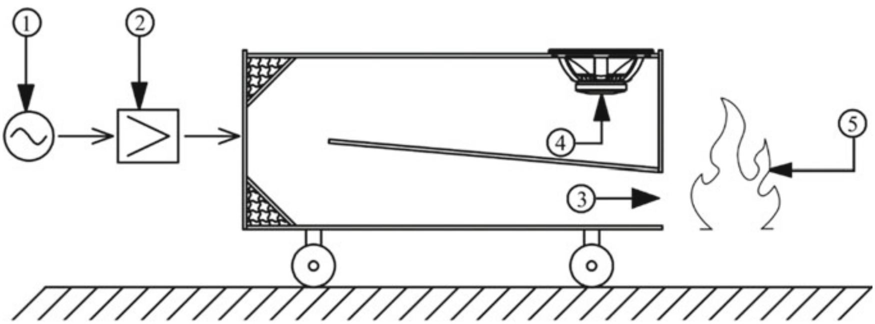

Fig. 16.1 Block diagram of the measurement station for testing extinguishing flames with the use of acoustic waves: (1) signal generator with AM modulator, (2) high and very high power amplifier, (3) waveguide (extinguisher) output, (4) loudspeaker, and (5) source of flames

B&C 21DS115 loudspeaker with a nominal power of 1700 W was installed at the beginning of the waveguide. The required waveguide length is two times smaller in the closed end tube in relation to the open tunnel [15]. For this reason, acoustic extinguisher was designed as the waveguide with tunnel bend with a rectangular cross-section of 428 cm in length. 1 V RMS was applied to the power amplifier input. The background noise level during measurements was equal to 64.7 dB. A professional trainer (fire mock-up) was used as a source of flames. This type of equipment is used by professional services investigating the possibilities of traditional fire extinguishers. The trainer was fuelled by propane–butane gas. Thus, during the experiments, the flames obtained as a result of igniting the gas were extinguished.

Apart from the application of high and very high acoustic power, a scientific novelty of the research is the presentation of the measurements results showing the possibilities of extinguishing flames using modulated waveforms. In this paper, AM modulation was used. The results show the sound pressure level (SPL) at which the flames were extinguished successfully as a function of the distance from the extinguisher output in the range from 50 to 130 cm, with a step of 10 cm, for a sinusoidal wave with a operational frequency $F_{OP} = 17.25$ Hz modulated by triangular waveform (AM modulation with frequency $F_{MOD} = F_{MFreq} = 0.125$ Hz). During the measurement, the peak value of the power supplied to the extinguisher was 1000 W. The waveform given from the generator to the power amplifier is presented in Fig. 16.2.

Measurements of sound pressure at which the flames were completely extinguished were carried out for both longitudinal and transverse positioning of the trainer. Measurement diagram for the longitudinal position of the trainer is presented in Fig. 16.3.

The following results of the experimental studies show the minimum sound pressure level (SPL) causing the successful extinguishing effect in the function of the distance (L) from the extinguisher output. There is an inversely proportional relationship between the decrease in sound pressure level and the increase in the distance from the waveguide (extinguisher) output. As the distance from the fire extinguisher

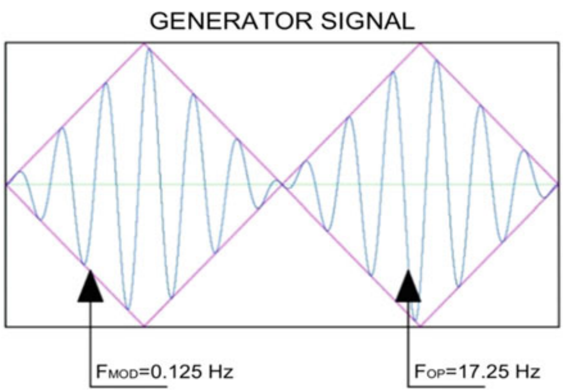

Fig. 16.2 Sine wave AM-modulated by triangular waveform

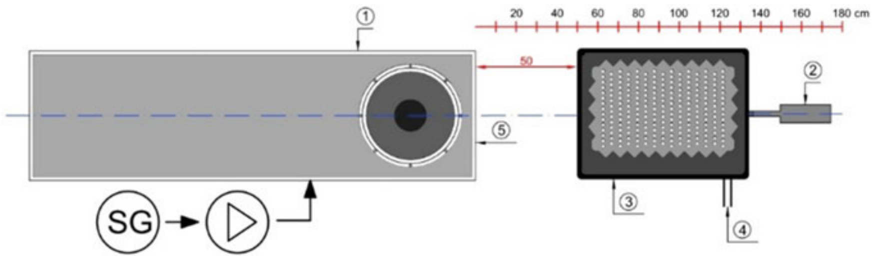

Fig. 16.3 Measurement diagram for the longitudinal position of the trainer: (1) acoustic extinguisher, (2) sound pressure level meter, (3) trainer, (4) propane inlet, and (5) extinguisher output

output increases, sound pressure level which is necessary to extinguish the flames decreases. The results showing the dependence of the extinguishing acoustic pressure as a function of the distance from the extinguisher output are shown in Fig. 16.4.

The measurement diagram for the transverse position of the trainer is presented in Fig. 16.5.

The minimum value of the sound pressure level (SPL) causing the successful extinguishing affect as a function of the distance from the extinguisher output is shown in Fig. 16.6.

As you can see, the minimum SPL causing the successful extinguishing effect as a function of the distance from the extinguisher output may be determined by the regression function (Figs. 16.4 and 16.6). On this basis it is possible to obtain the trend functions of the SPL from the extinguisher output within the analyzed distance range (the curves called "trendline") and their character. Thus, it is possible to determine the approximate values of the sound pressure level causing extinguishing effects for other distances. Trends can be distinguished using the method of mechanical time series

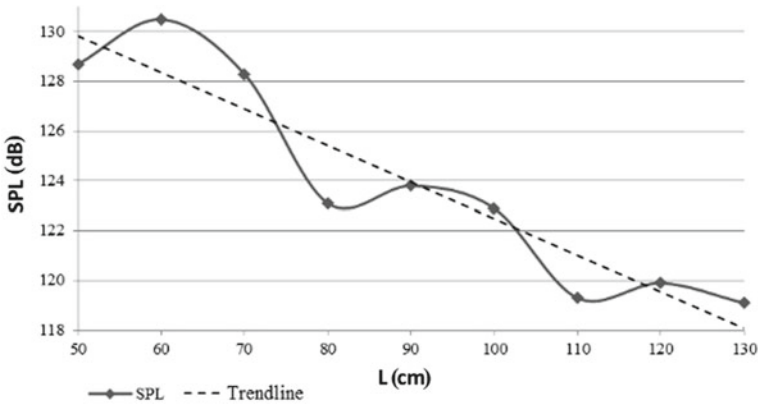

Fig. 16.4 Dependence of the sound pressure level as a function of the distance from the extinguisher output for the longitudinal position of the trainer

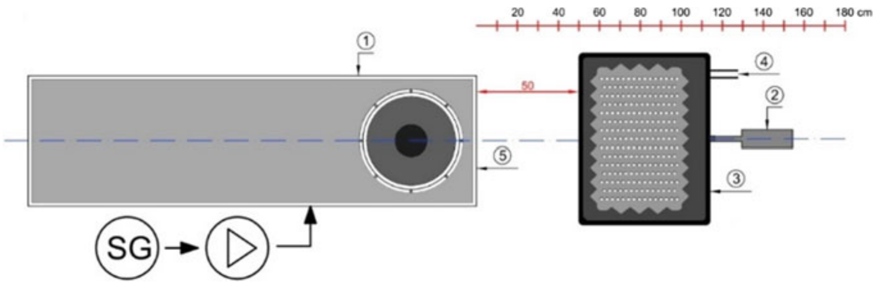

Fig. 16.5 Measurement diagram for the transverse position of the trainer: (1) acoustic extinguisher, (2) sound pressure level meter, (3) trainer, (4) propane Inlet, and (5) extinguisher output

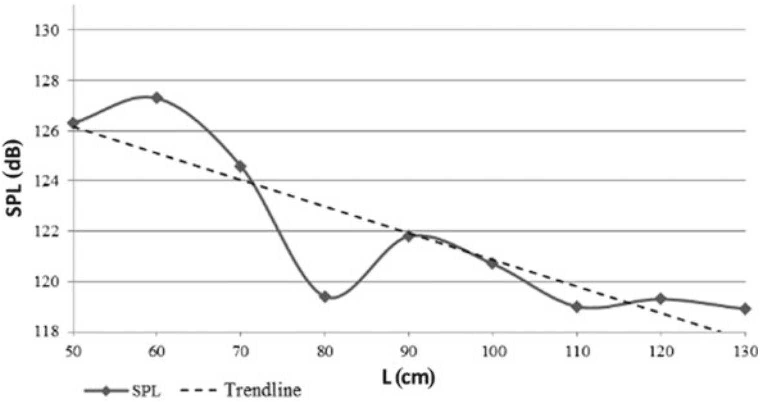

Fig. 16.6 Dependence of the sound pressure as a function of the distance from the extinguisher output for the transverse position of the trainer

alignment or the analytical method based on empirical data. For this purpose, the authors used the analytical method of extracting the developmental trend by adjusting the specific mathematical function to the time series. The linear trend function was used as a function of the development trend and if it is necessary the parameters can be estimated using the method of least squares.

16.3 Using Deep Neural Networks for Fire Detection

16.3.1 Hardware System for Fire Detection and Control of Fire Extinguisher

The proposed system consists of low-cost computer module, USB camera, and Movidius stick for implementation of deep neural network for fire detection (Fig. 16.7). The system is responsible for flames source detection and can be connected to the acoustic fire extinguisher and its activating.

The hardware is based on a Raspberry Pi board which has a quad Core 1.2 GHz Broadcom BCM2837 64 bit CPU, 1 GB RAM, plenty of communication capabilities, camera slot, and display port. The board can support various operating systems (OS) like: Ubuntu, Raspbian, Windows 10 IoT. The video controller can support modern resolution standards such as HD and Full HD. It can also generate 576i and 480i composite video signals for PAL-BGHID, PAL-M, PAL-N, NTSC, and NTSC-J.

An USB camera Logitech C310 is connected to the Raspberry Pi providing 1280 × 720 pixels resolution. It guarantees a 30fps video signal and has a fixed focus and 60º field of view. This USB camera is selected because of its price and the good quality of the output video signal.

The Movidius stick is vision processing unit (VPU) that uses specialized processor with high computing capacity to perform complex operations on static and dynamic data using artificial neural networks. The direct communication between the Raspberry Pi and the Movidius VPU module allows to be achieved a significant acceleration of processing performance. This acceleration is due to the lack of complex computational operations inherent from deep neural network which has to be processed in the Raspberry Pi. The Movidius USB stick increases the performance by integrating the neural network that performs the math computations using the so-called vision processing unit—Myriad 2. This type of processor is specifically designed for tasks related to machine vision and it is also very energy efficient. The proposed system incorporates LCD display for visualization of video stream from

Fig. 16.7 Hardware system for fire detection **a** structure and **b** final system

camera and for drawing of contours of the fire sources and flames that are found in the video signal. To control the extinguisher, two relay modules are used. They send 24 V control signals to the acoustic extinguisher depending on presence of fire in the video stream.

Several software technologies are used in the process of fire detection as: OpenCV, NumPy, Matplotlib, Imutils, and TensorFlow.

16.3.2 Training of the DNN

The neural network used in developed system is based on MobileNet architecture, which has a high speed of object detection. The MobileNet is an architecture that is suitable for mobile and embedded applications. It was developed by Google.

The training requires a preliminary database of pictures from which the DNN will retrieve the characteristics of the fire objects which should be found afterwards. The neural network is initially capable of recognizing multiple objects and by replacing some layers it can be trained to recognize specifically which part in the image is fire. The mentioned neural network is trained using the TensorFlow Machine Learning Library using more than 250 images of fire, which are freely available in the Internet. Initially, the fires (and their position in the image) have to be labeled manually before the training process. A Python scripts generates 1000 shifted and scaled images from the mentioned above also with supporting information for the coordinates of fires in the images. These images are saved in “png” format and used for training of the network.

Figure 16.8 presents some of the images used in the training process.

Fig. 16.8 Some of the images used for training of the deep neural network

The neural network expects in its input layer images with format 300 × 300 × 3 (300 × 300 pixels × 3 colors). Therefore, all training images are scaled to have such resolution. The training process continues 200,000 epochs with batch size of 24 images. The training is done with GPU device GTX 1080 Ti and it takes 8 h to complete.

16.4 Experimental Results

After the successful training, the well-trained neural network is implemented in the Movidius USB stick. The arrays of fire of burning objects are further processed in the Raspberry Pi and their positions are marked on the images. The trained network is able to detect fire under different conditions of the background. The neural network was tested with 100 test images which were not included in training process. The precision is 93%. Figure 16.9 presents some of the test images and the fire detected in it.

To be sure that the neural network is properly trained, it is necessary to test it with images captured by the Web camera connected to Raspberry Pi. The color video stream from the camera with resolution 1280 × 720 pixels is scaled to have resolution 300 × 300 pixels and after that the video frames are supplied to the input of the neural network. The fire sources in the video stream are recognized successfully by the trained deep neural network. Figure 16.10 presents a fire detection process using the real time acquisition of images of fire.

Fig. 16.9 Some of the images used for testing

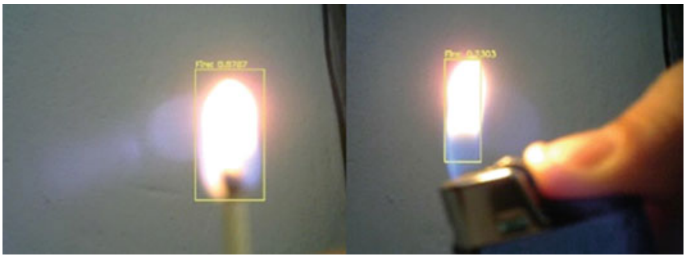

Fig. 16.10 Images from camera for real-time testing

The testing for "false positive" reaction of the system was done in different rooms under different lightning conditions—direct sunlight in the room, artificial light, and low level of light intensity. In all tests, the system does not demonstrate "false positive" detection of fire.

All the experimental results received during the test of the deep neural network prove its suitability for fire detection. The system (based on Movidius and Raspberry Pi) can be used successfully as smart system for fire detection and control of acoustic fire extinguisher. When the fire is detected, the system can generate signal for activation of acoustic extinguisher. In this case, Raspberry Pi board switches on two relay modules which activate the power supplies of signal generator and power amplifier used in the construction of the acoustic fire extinguisher.

16.5 Summary

In the long-term perspective, the technology of extinguishing flames using acoustic waves' extinguishers controlled by neural networks, proposed by the authors, can be permanently implemented in various devices including buildings or transport (both land, water, and air transport means). Contemporary research on flame detection using neural networks is crucial in this respect. Moreover, the technology of extinguishing flames with acoustic waves may support the fire protection of halls, warehouses, or liquid tanks. The big advantages of this solution are significantly lower costs of extinguishing and operation (what was mentioned earlier) in relation to traditional extinguishers. The results of current paper can be used as basis in future research where the DNN for fire detection will be used for control of autonomous acoustic fire extinguisher which will be able to react independently when fires are detected.

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