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INFRARED THERMOGRAPHY IN THE CONTEXT OF FIRE SAFETY IN CONTAINER TRANSPORTATION BY SEA

ІНФРАЧЕРВОНА ТЕРМОГРАФІЯ У КОНТЕКСТІ ПОЖЕЖНОЇ БЕЗПЕКИ КОНТЕЙНЕРНИХ ПЕРЕВЕЗЕНЬ МОРЕМ

V. Konon, *PhD student,* **V. Savchuk**, *professor, PhD.*

В.В. Конон, *аспірант,* **В.Д. Савчук**, *к.т.н, професор*

National University "Odessa Maritime Academy", Ukraine

Національний Університет «Одеська Морська Академія», Україна

ABSTRACT

The given study focuses on the issue of marine fire safety systems as well as their improvement on container vessels. Modern technologies and a fresh look at the problem may significantly improve the methods and equipment for efficient and early reaction to hazardous situations' development and/or their full prevention. In connection with the increase in the carrying capacity of container ships, the problem of the safe transportation of containers, and particularly the transportation of IMDG cargo, becomes more relevant. Therefore, in order to combine the advantages of existing fire protection systems with new perspectives in this regard, the concept of thermographic tools application was proposed, particularly for cargo carried under the deck. In the course of the work, the cargo state observations using a thermal camera were demonstrated. The preliminary effectiveness of the concept was evaluated, highlighting the importance of proper equipment calibration for more accurate results. To conduct an experimental assessment within the framework of the task, it was decided to use the simulation modelling methodology with the help of the designated integrated development environment (IDE) and C# programming language capabilities. The developed model gives an opportunity for further research in the field, describing the algorithm for processing the obtained data in order to comply with the framework of the main task. As such an algorithm, the use of a multilayer perceptron is proposed.

Keywords: thermal imager, infrared thermography, fire safety, container transportation, neural networks, simulation modelling.

РЕФЕРАТ

Поточні дослідження зосереджені на проблемі морських систем протипожежної безпеки, а також їх удосконалення на контейнеровозах. Сучасні технології та свіжий погляд на поставлену проблему, можуть дати суттєве вдосконалення методів та обладнання для ефективного та раннього реагування на розвиток небезпечних ситуацій та/або повного їх запобігання. У зв'язку зі збільшенням вантажопідйомності контейнеровозів все більшої актуальності набуває проблема безпечного перевезення контейнерів, зокрема перевезення небезпечних вантажів. Таким чином, було запропоновано використовувати термографічні інструменти, особливо для вантажів, що перевозяться під палубою, щоб поєднати переваги існуючих систем протипожежного захисту з новими пропозиціями в цьому відношенні. В ході роботи було продемонстровано спостереження за станом вантажу за допомогою тепловізора, оцінено його ефективність і зроблено висновки щодо важливості правильного калібрування обладнання для отримання коректних результатів. Для проведення експерименту в рамках завдання було вирішено використати методологію імітаційного моделювання з використанням інтегрованого середовища розробки та можливостей мови програмування C#. Розроблена модель дає можливість для подальших досліджень у цій галузі: описання алгоритму обробки отриманих даних з відповідністю до мети основного завдання. В якості такого алгоритму пропонується використовувати багатошаровий персептрон.

Ключові слова: тепловізор, інфрачервона термографія, пожежна безпека, контейнерні перевезення, нейронні мережі, імітаційне моделювання.

Defining the general matter and its connection to important scientific or practical objectives

Container transportations occupy more than 90% of the non-bulk cargo market [1]. The growing demand for container shipping in recent years resulted in the supply of the world's container fleet with ultra-large container ships (ULCS). However, despite the enlarged size, commercial issues, such as decreasing the number of crews onboard, frequently prevail over safety issues, which is confirmed by practice. In other words, the number of a container ship crew of 3,000 TEUs may have a very slight difference from the number of crewmembers on a ship with a capacity of 14,000 or more TEUs. According to the studies presented in [2, 4], which are based on the EMSA database and other publications, it can be interpreted, that from a safety point of view, the design of ULCS' is founded on the same principles as for ships of smaller sizes. In this way, it was expected that such an approach could perform designated functions with a relevant fraction of efficiency. The combination of such factors leads, for example, to the growth of the workload on crews, which logically provokes the risks of emergencies to be increased, particularly, aggravating the harmful effects of the human factor. Besides, the high workload level applies to all areas of the crew's activities: from maintenance of the vessel, her equipment, and machinery, to the control of the transportation process safety, namely, monitoring the condition of the cargo. Particular attention in this aspect is given to special cargo such as refrigerated or dangerous goods. The transportation of dangerous goods carries inherent risks that can lead to emergencies of a serious nature, endangering not only the ship herself and the goods carried, but more importantly, people's lives. According to [1] 58% of 36 contributing factors in twelve reports connected with fire/explosion cases refer to emergency handling onboard during emergency response, malfunctioning of the equipment and/or its installation/design, and wrongly declared or missing information on IMDG cargo. There are many researches such as [3] considering containers’ fire resistance, their properties and improvement proposals, etc. However, in our opinion, the safest fighting method is the prevention of the occurrence in roots. In other words, firefighting seems to be more efficient at the early stages of emergency development, so early detection methods and/or principles should be involved and modified, where applicable. In this way, the current study focuses on the onboard fire safety systems, as well as their improvement in terms of their use on container ships. Modern technologies and a fresh look at the problem issued may give a significant improvement to methods and equipment for efficient and early reaction on hazardous situations development and/or their full prevention.

Previous researches analysis and definition of new trends in problem solution

The following researches state the problem of insufficient productivity of present fire-detection systems, proposing various improvement ways. In work [5] the new way of communications flow is presented, proving datasets as the result, which are proposed to be used in deep learning techniques of machine learning with the purpose of improving early fire detection procedures. A study [6] suggests the use of pyro-electric infrared (PIR) sensors for real-time fire detection with applying of digital neural networks (DNN). Neural networks as a model, although known since the previous century [8], found a new life nowadays with the progress of computing power of modern digital devices. Works [5, 6, 12] similar to numerous types of research implement different variations of such an algorithm, considering this as an effective way of computer data processing, seriously enhancing the issue in general.

However, DNN is not a panacea, despite all of the advantages, there is a sequence of factors, which impose the effectiveness of the method. Current research is concentrated on marine fire systems and does not claim other fields. Mentioned factors include, but are not limited to, the following:

- The sensors used.

- The circumstances and conditions of application. For example, whether a system is designed considering a specific vessel environment or not, and if it is – the respective limitations, such as whether could it be applied both on deck and cargo spaces etc.
- The algorithms and data for DNN. Data quality and amounts for neural network training considering specified tasks have a high influence on the expected results [9].

The principles for video fire detection systems are discussed and proposed, describing algorithms of image processing for early smoke detection in [7, 11] and video flame detection in [10].

Thermal imaging provides a wide variety of applications, such as agriculture, medicine, investigation, fire safety and security. In the aspect of fire detection systems, thermography can assist in the recognition of dangerous tendencies before they could be detected by other sensor types. One of the advantages is the ability to see through the smoke, which is useful for fire source localization. In addition, it found wide application by fire-fighting teams for people searching [13]. Although thermal cameras may not be as much accurate as contact sensors, nowadays they gain more and more popularity. Modern thermal cameras combine visual and thermographic data, providing an opportunity for its proper processing and use. This peculiarity allows uniting the advantages of video fire detection systems with other types (such as described in [6], using PIR sensors), granting more information for analysis and opportunities for cross-control, which are especially important in the maritime field. Additionally, MATLAB software provides tools for real-time image/video processing and computer vision [14]. Summarizing the above-mentioned, thermal imaging could be used as an efficient and useful tool in terms of early-stage fire detection.

The research objective

The main goal of this work is to propose a concept of thermal imaging application in marine fire-fighting systems onboard container vessels with regard to IMDG cargo transportation.

Presenting the main material of a research with a full grounding of received scientific results

1. Thermography application research and performance results.

At the initial stage of the research concept development, observations of thermal camera operation were carried out in order to identify data available for collection and processing within the framework of the task, resulting in receiving thermal images. A thermal image is a visual picture of thermal radiation captured by an IR matrix. Colour charts (palettes) are often used to visualize data for the operator. Palettes are required for a better match of pixels' intensity values, resulting in better image detail [13]. As an example, the photos of the vessel's perspective (C/V "Cap San Artemissio") are shown below for visualization purposes in thermal and visible (fig.1) spectrums.

Figure 1. Image of the vessel (infrared and visible spectrums)

Infrared radiation (IR) lies in the range between visible light and the microwave range of the electromagnetic spectrum [15]. It covers the wavelength range from 0.76 to 1000 µm. Any object with a temperature above absolute zero (-273.15°C or 0 Kelvin) emits radiation in the infrared region. It means that objects which seem very cold relative to human perception, such as ice cubes, also emit

IR rays. In other words, if the human eye could see in the IR range, then the temperature of objects could be estimated without tactile contact.

Thermal optical equipment is very similar to conventional optics and works on similar principles [16]. One of the fundamental construction differences is the glass material. Ordinary glass does not conduct infrared waves through itself. Therefore, to resolve this issue, lenses for thermal devices are made using special materials and frequently from rather expensive germanium. A detector that captures infrared radiation and converts it into information, as in a conventional camera, consists of a sensitive matrix and an electronics unit that processes the signal. Through a system of lenses, infrared radiation is fed to the matrix and then the processor converts the data into a video signal, which afterwards is sent to the screen of the device (fig.2).

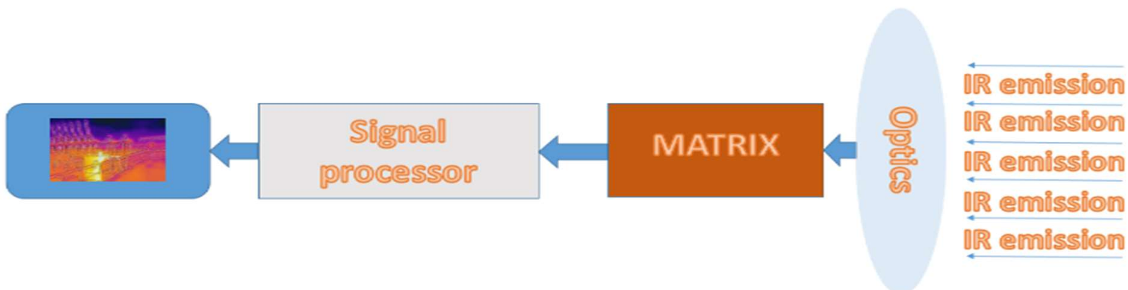

Figure 2. Simplified block diagram of thermal camera operation

Compared to night vision devices, a thermal imager is a more versatile and at the same time more complex tool. For example, the night vision device forms an image based on the light reflected from the object. It means, that an operator will not be able to find a black-coloured one in a completely dark isolated room using such equipment. On the contrary, with the help of a thermal imager, such an object could be found easily. In simplified form, a certain temperature of the resulting image is associated with each of its pixels, so a temperature matrix can be obtained and such data could be used for further processing. Usually, that operation can be carried out using the appropriate software provided by the device's manufacturer. Specifications of the thermal module used in the research are presented in Table 1.

According to Kirchhoff's rules, the IR-emission which is received by a thermal imager consists of emerging, reflected and transmitted (through the object) long-wave IR radiation components [15, 17]:

$$\varepsilon + \rho + \tau = 1, \tag{1}$$

where ε, ρ, τ – emissivity, reflectance and transmittance respectively.

According to [15]: "..*Most solid bodies do not transmit thermal radiation, so that for many applied problems the transmissivity may be taken as zero*" and *"…as transmission rarely plays a role in practice, the transmission τ is omitted…*[17]", so the formula (1) can be simplified to the next form:

$$\varepsilon + \rho = 1 \tag{2}$$

The emissivity and temperature of the reflected radiation can be set manually in the thermal imager.

During the research temperature data was obtained (samples in fig.3, 4), and it was concluded, that from a practical point of view, the use of such cameras, could be rather effective and necessary for dangerous goods transportation inside cargo holds to ensure the constant monitoring of their condition. Thus, the task focuses on the development of an algorithm for the early detection of a fire as well as its source. For this purpose, firstly, the positions scheme should be designed for the thermal cameras to ensure an effective area is captured. Secondly, the most efficient way of processing the obtained data should be defined accordingly, providing real-time monitoring and assessment of the developing situation.

Table 1. Thermal camera module specifications

Camera module	
Thermal resolution	*80x60*
Visual resolution	*640x480*
HFOV / VFOV	*46° ± 1° / 35° ± 1°*
Radiometry	
Scene dynamic range	*-20°C – 120°C*
Accuracy	*±5°C or ±5%* *Per cent of the difference between ambient and scene temperature. Applicable 60s after start-up when the unit is within 15°C – 35°C and the scene is within 10°C – 120°C.*
Image Format	*Thermal (MSX) and visual as radiometric jpeg*
Thermal Image Analytics	*- Movable spot meters* *- Whole image ROI* *- Editable in saved images*
Palettes	*Iron, Black hot, White hot, Rainbow, Contrast, Arctic, Lava, Coldest, Hottest*

As it was already mentioned above, the thermal data layer of the image allows better analysis using a special software environment provided by the device's manufacturer with various reports generation, data export functions, etc. For example, temperature measurements may be taken at different spot meters of the same image (marked with "Sp" on fig. 3, 4), as well as general data of the frame (e.g. minimum, maximum and average values), providing parameters for editing, namely emissivity, reflected and ambient temperatures, ambient humidity, dynamic properties of the optics, etc. The proper calibration of the thermal imager provides receiving more accurate results. In some cases, particularly when ambient temperature differs significantly from the temperature of the object being measured, proper emissivity setting becomes a critical factor inherent to the calibration process.

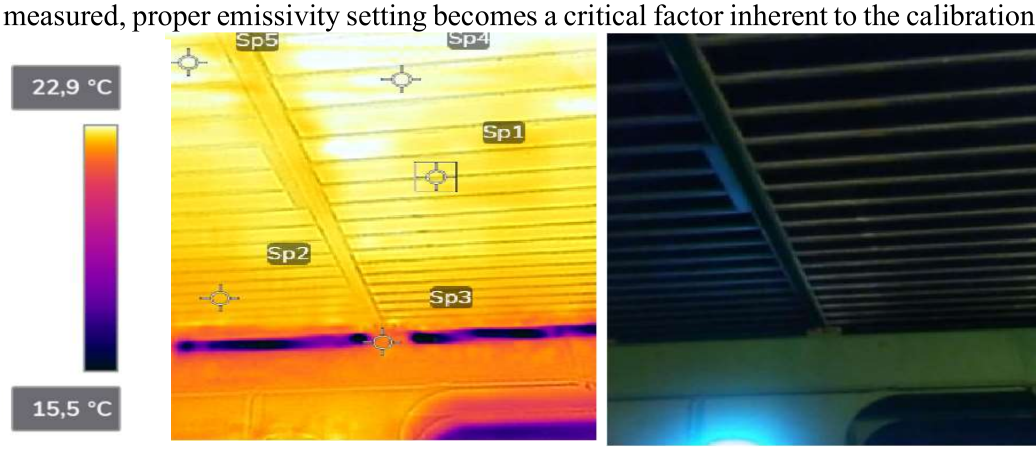

Figure 3. Cargo container on deck (infrared and visible spectrums)

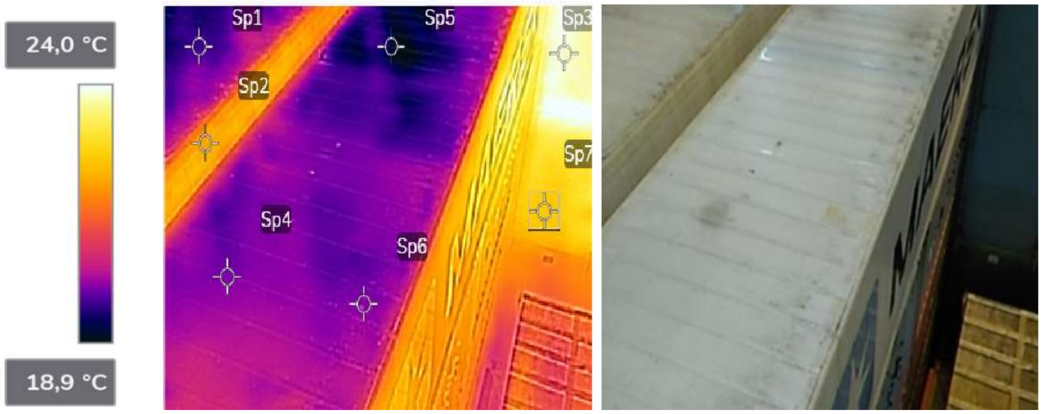

Figure 4. Cargo container in cargo hold (infrared and visible spectrums)

The results of the measurements obtained during observations presented in the fig. 3 and 4, are summarized below in the table form (Table 2).

Table 2. Measurement results relevant to figures 3 and 4

Parameters	**Deck**	**Hold**	**Parameters**	**Deck**	**Hold**
Temperature measurements, °C					
Max	*23.8*	*25.1*	Sp3	*22.5*	*24.7*
Min	*14*	*19.1*	Sp4	*22.9*	*20.5*
Avg.	*22,9*	*21.4*	Sp5	*22.8*	*19.4*
Sp1*	*22.6*	*20.1*	Sp6	-	*22.6*
Sp2	*22.7*	*22.8*	Sp7	-	*25.1*
Other parameters					
Emissivity			*0.8*		
Reflected temp., °C			*22*		

* *“Sp” - spot. Referred to the corresponding spot meters in fig. 3 and 4.*

Taking into account the lack of extraneous external factors, the temperature of the measured objects tended to the ambient temperature (average values are less than ±1°C in shown examples), considering the measurement error of the instrument in use, the results obtained can be appraised acceptable within the framework of the task.

In the diagram below (fig.5) potential measurement results relevant to cargo hold observations (fig.4) for various emissivity settings are presented, illustrating the dependency of temperature values on the mentioned coefficient, which confirms the importance of proper thermal camera calibration.

It should be clarified, that the temperatures shown in figure 5 do not correspond to the real measurements and conditions which are applicable to figure 4. The real emissivity setting for the described case is 0.8, which is noted in Table 2. Abnormal values of temperatures for the diagram below were obtained through manual emission setup during the image processing by means of the camera manufacturer`s software. In general, although software capabilities may be different, the main functionality includes, but is not limited to:

- Data import and export.
- Thermographic data analysis and processing.
- Report creation tools for the summarizing of the results.
- Report exporting tools for further use (optionally, an opportunity of saving in different formats).
- Manual parameters setting to fit specific conditions.

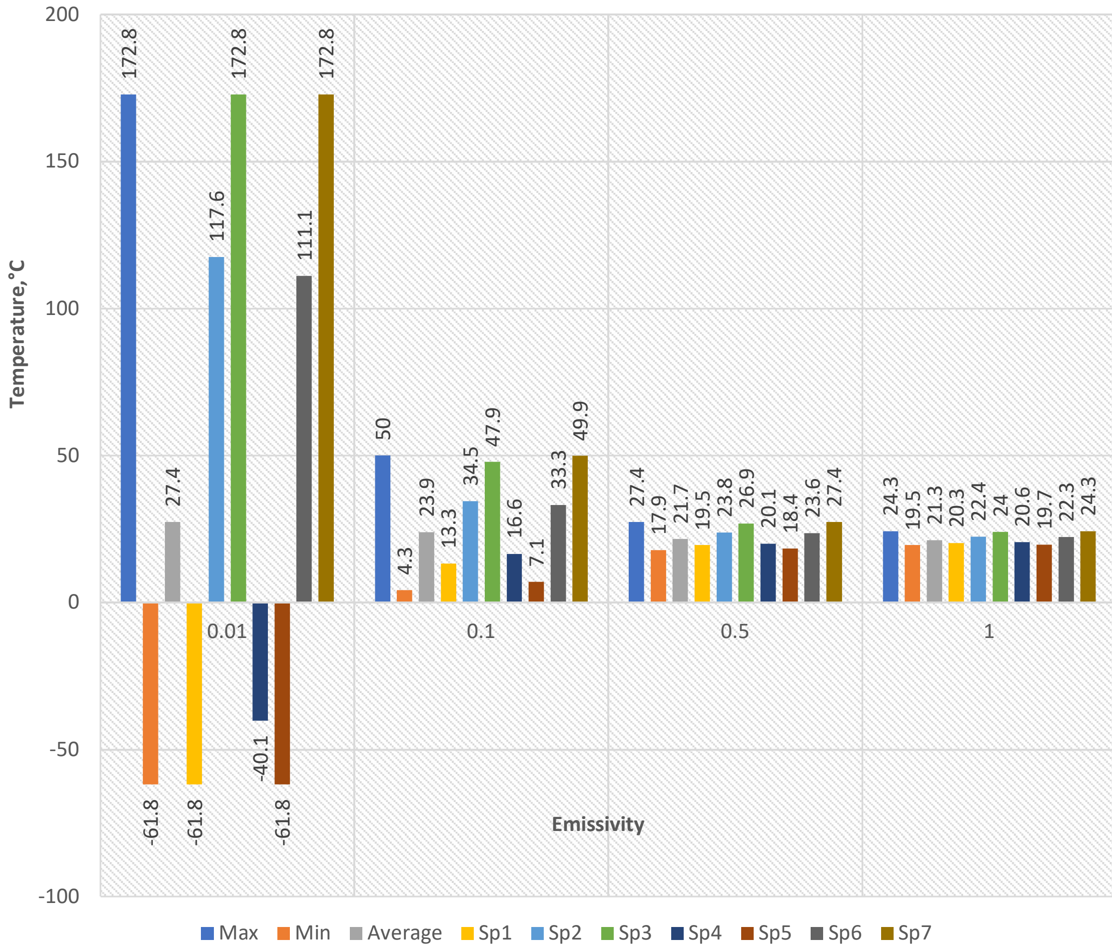

Figure 5. Dependencies of the temperature values on the set emissivity coefficient

Please note that values of $\varepsilon = 0{,}01$ and $\varepsilon = 1$ are theoretical and shown for better visualization of the subject and for reference only (when $\varepsilon = 0$, a material can be considered a perfect thermal mirror). From the diagram, when $\varepsilon = 0{,}01$, temperature values may even exceed IR - matrix limitations (see table 1). This fact additionally proves that the error, which can potentially occur, may be significant, where set parameters are far from real materials properties and ambient conditions.

2. Simulation modelling

Nowadays simulation modelling is widely used in several fields. The undeniable advantages of simulation modelling are:

1) Economic benefits.
2) Relative reduction in the time of preparatory operations;
3) Timely and safe correction of experimental errors without endangering people's health and damage to property, which is an important argument within the framework of the task.

Taking into account the above-mentioned, it was decided to conduct the experiments in such a format. Considering the purpose of the research, to simulate the expected necessary conditions, the designated integrated development environment (IDE) software in combination with C# programming language capabilities was used. The simulation scene (fig. 6) presents the overall view of the cargo hold space, without specifying thermal camera positions, as the current article is focused on the concept of thermal imaging applications for the purpose of fire detection and prevention systems onboard container vessels.

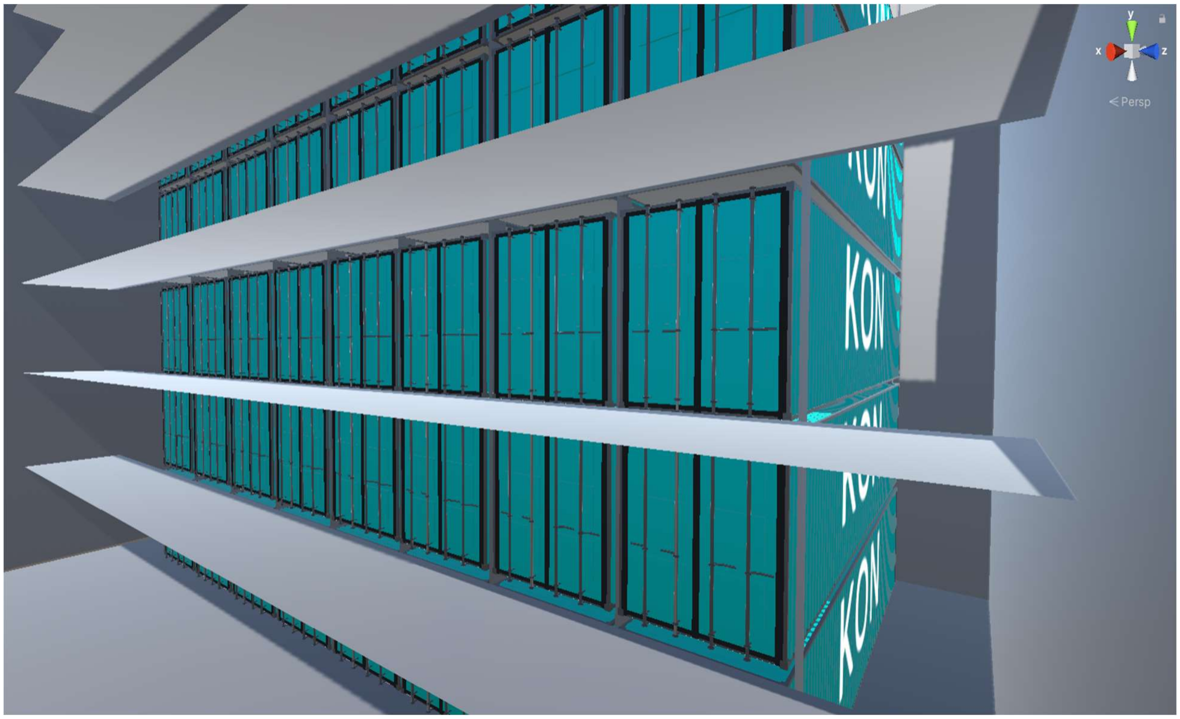

Figure 6. Cargo hold simulation

Estimating the volumes of potential information to be analyzed (containers loading degree, thermal conductivity of cargoes, uniformity and heterogeneity of loading, heat losses, development of secondary heat sources, etc.) and objects' interactions to be implemented into the simulation, next limitations have been applied to the model, without restrictions for solving the issues within the framework of the task:

1) quantity of containers in simulation shall be enough to provide a full examination of the simulated process within a 40-feet cargo hold bay;
2) loading pattern shall consist of containers of the same size (40 feet units);
3) containers, except the one in which the ignition source is located, shall be considered empty to avoid additional issues, that can unnecessarily complicate the task and/or be an issue for separate research;
4) temperature palette should be distinctive enough to ensure a proper visualization of the process;
5) heat exchange model should satisfy the objectives of the task, namely, the application of thermal imagers in the context of enhancing marine fire safety systems.

In the developed simulation model, each side of the container is considered as some conditional plane, divided into a certain number of segments. Each segment interacts with another adjacent segment so that in accordance with a given functional dependency, the temperature value changes from segment to segment. The colour change is implemented via separate functional dependency for several temperature intervals. The current simulation is considered acceptable for satisfying the above-mentioned requirements, and applicable for designing an appropriate camera allocation pattern to achieve effective early-stage fire detection. Heat exchange simulation is presented as follows:

1) 40-feet container bay with a sufficient number of containers is available for the examination of the simulation process in the context of the task's framework;
2) only 40-feet units were used for simulation;
3) all containers in the simulation are considered empty, except the one with a fire source;
4) temperature palette and heat exchange model satisfy the requirements for the task objective (fig.7).

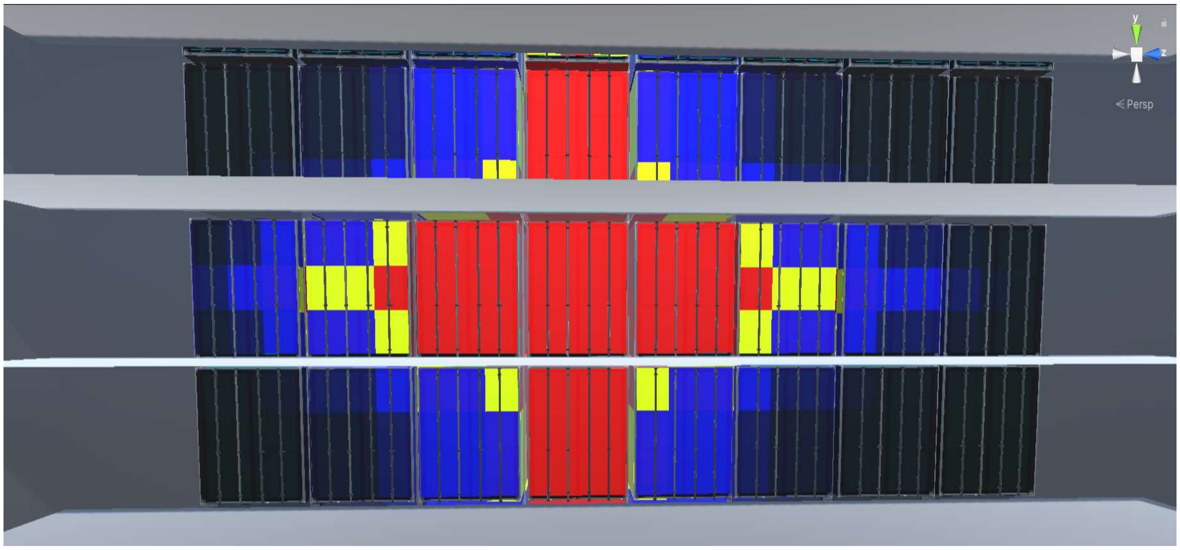

Figure 7. Heat exchange simulation

Further research prospects are the design of the efficient thermal cameras allocation in the way they can cover the effective area under the deck in row-tier plane, leading to the following task of an algorithm creation that would be able to predict the potential development of the hazardous situation. In addition, the expected algorithm should be able to estimate the fire source location with sufficient probability. Thus, a multi-layered perceptron (or of a similar kind) mechanism is suggested for an application in the current context (fig. 8). The input data of the perceptron should receive thermal imagers' output data in real-time mode. Some other parameters may be added in order to obtain more accurate results.

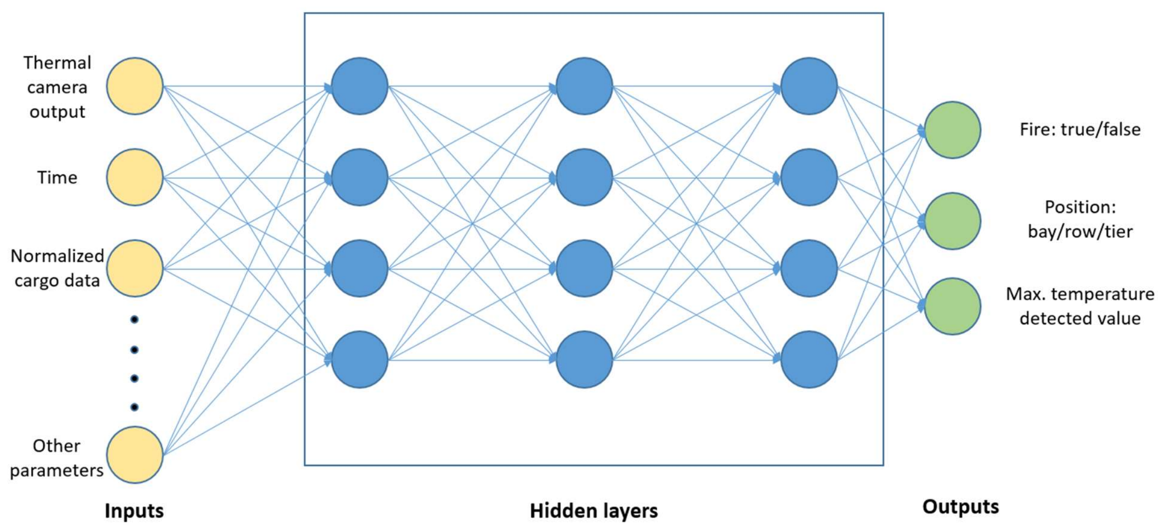

Figure 8. Multilayer perceptron schematic view (concept)

A multilayer perceptron is a digital neural network consisting of layers: input layer, hidden (learnable layers) and output layers [18]. Each layer consists of elements - neurons (a digital model based on a biological neuron idea). Unlike the single-layer version, this type contains several trainable hidden layers instead of only one, which allows for solving complex tasks with higher efficiency. A digital neuron represents a network element that has several inputs with a weighting coefficient for each. A neuron, receiving a signal, multiplies it by respective weight and then summarizes all the products. Afterwards, the final result is transmitted to another neuron or the network output.

Conclusions and further research prospects

In connection with the increase in the carrying capacity of container ships, the problem of the safe transportation of containers, and in particular the transportation of IMDG cargo, is becoming more relevant. In order to prevent the occurrence of dangerous situations and/or their early detection, it was proposed to use thermographic tools, namely for cargo carried under the deck, in order to combine the advantages of existing fire protection systems with new perspectives. In addition, the expansion and diversity of the existing variety of marine fire systems in this context could assist to increase the level of automation of the cargo control process reducing the workload on ship crews and the influence of human factors in this matter. Thermal imaging is widely used in various fields, e.g. agriculture, medicine, investigation, fire safety, security, etc. The advantages of thermal imaging were described in this work.

Based on the observations, it was concluded that the results obtained could be assessed as acceptable in the terms of the task. Particular attention shall be paid to the calibration, as the improper emissivity setting may significantly reduce the accuracy of the results, particularly when ambient temperature largely differs from the temperature of the object being monitored.

Taking into account the undeniable advantages of simulation modelling and considering the purpose of the research, to simulate the necessary conditions, designated IDE in combination with C# programming language capabilities was used. Understanding the volumes of potential information to be analyzed and objects' interactions to be implemented into the simulation, several limitations have been applied to the model. Heat exchange simulation was presented in accordance with the limitations imposed. A multilayered perceptron algorithm has been suggested in order to process the thermal imagers' output data in combination with other parameters for sufficient and accurate fire occurrence determination and/or prevention. Further research on the subject will be focused on the following issues:

1) Description of the thermal imagers' allocation scheme covering the effective area under the deck.
2) Extraction of the necessary and sufficient data, followed by its processing.
3) Neural network learning.
4) Definition of the advantages and disadvantages of the developed model.
5) Implementation of the corrective measures into the framework of the research.

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