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Drone-based Fire Prevention System on Container Terminals - A Theoretical Study

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ABSTRACT: The article presents the proposition of developing an innovative fire detection system, based on unmanned aerial vehicles and multiple sensors. The paper contains short review of recent literature related to the topic, current state of fire prevention policy at the container terminals, scoping on the Polish seaports. To prove the necessity of the improvement of fire detection methods it has been described the fire incidents from recent years. The article also outlines the design assumptions of the proposed system as well as the theoretical workflow. Potential issues, further improvements and prospect have been pointed.

1 INTRODUCTION

Cargo storage and handling operations have always generated the risk of fire. The containerization has increased safety as the goods were separated from each other with solid walls of the container. However, there may be dangerous goods inside, some of which could pose a risk of a fire ignition. There is also a special type of container that is capable of storing perishable cargo. This type of refrigerated container is equipped with the aggregate that maintains a constant, low temperature inside but generates heat outside of the container. Taking this into consideration, the risk of fire remains at non-zero level. The conclusion could be made that it would be useful to develop a universal, autonomous or semi-autonomous fire detection or fire prevention system. This article aims to outline the theoretical concept of one of them.

The paper is divided into four paragraphs, excluding introduction and conclusion:

- literature review - short description of the papers and research related to the topic, published in recent years,
- fire prevention policy at container terminals - the paragraph contains short description of Polish container terminals, applicable regulations with the citations of proper documents and the fire prevention methods maintain in the terminals,
- outlining the problem – fire incidents in seaports and container terminals - it contains fire incidents that occurs in recent years,
- fire prevention system - this paragraph presents the concept of the proposed system, including the operation algorithm.

This article is an introduction to further research and development process of creating the system that fulfills stated requirements.

2 LITERATURE REVIEW

Articles related to the topic can be divided into three categories:

- use of drones and robots for firefighting and fire prevention operations;

– risk assessment and safety management at seaports and terminals;
– fire prevention and firefighting systems on vessels.

It is hard to find a study that combines these categories. Alon, Rabinovich, Fyodorov and Cauchard in [1] present a user-centered perspective on the integration of semi-autonomous drones in firefighting. In [2] Bogue shows details of recently developed firefighting robots and their applications. Roldán-Gómez, González-Gironda and Barrientos proposed a multi-robots firefighting support system based on drones swarm [9]. In the described system, groups of drones were used for prevention, surveillance and extinguishing fire. Apart from the drones the system also uses the Virtual Reality (VR) and Augmented Reality (AR) interfaces to manage control and provide quick and convenient information exchange between mission commander, team leaders and team members in the field of operation. In [4] - Jin, Kim and Moon present a development of a firefighting drone capable of suppressing nascent low-intensity fires.

Ngo Van Nam presents the analysis of fire prevention operations and systems in Vietnam [8]. His paper shows statistics of legal actions taken in the last few years by ports and Vietnam authorities to increase fire safety. The article also points out some recommendations and advice for further work on the described topic. The authors of [7] provide a comprehensive analysis of the status of the risk assessment process and its associated methods at Baltic Sea Region major seaports. Christowa in [3] performs identification and analysis of threats in Polish seaports.

The authors of the [6] analysed the fire incidents that occurred on the container ships during the past decade. They focused on 23 cases and presented a detailed description of each of them. The paper includes dates of incidents, locations on the vessels where each fire broke out, the causes of fires and the extent of the damage. There is also information about methods used to extinguish the fire, the number of victims and whether external help was necessary. In the conclusions the authors point out the statistics resulting from their work and propose possible solutions to the described problem.

3 FIRE PREVENTION POLICY AT CONTAINER TERMINALS

3.1 *Polish container terminals*

A container terminal is a complex used for handling containers - transshipment from various means of transport in order to continue their journey or storage in yards. This can take place both between ships and wheeled vehicles (trucks and trains). In this case we are talking about a maritime container terminal, which is usually located close to or even inside larger cities, as well as being part of a larger port infrastructure.

In Tri-City area we can distinguish two main container hubs:
– Baltic Hub (Container Terminal at the Szczecin Quay) in Gdańsk [Fig. 1]
– GCT (Gdynia Container Terminal) and BCT (Baltic Container Terminal) in Gdynia [Fig. 2]

Figure 1. Baltic Hub, image source: https://www.bankier.pl/wiadomosc/Ruszyla-rozbudowa-terminalu-Baltic-Hub-w-Gdansku-warta-ok-2-mld-zl-8447249.html last accesed 19/03/2025

Figure 2. Baltic Container Terminal, image source: own collection

3.2 *Applicable regulations*

The transshipment and transport of goods in containers cannot take place without the risk of transporting dangerous goods, which must be "transported" from one place to another, most often using sea transport, and therefore stored in port container terminals. This can lead to dangerous situations, which port authorities try to prevent as much as possible. The IMDG Convention (International Maritime Dangerous Goods Code) - the International Dangerous Goods Code, i.e. the code for the safe transport of dangerous goods by sea issued by the IMO (International Maritime Organization) and updated every two years. It divides goods into dangerous classes, regulates and standardizes issues of packaging, marking of goods during transport, as well as their placement on ships. Additionally, you can also find guides there (e.g. first aid in the event of human

exposure to hazardous substances), a list of procedures in the event of a fire of dangerous substances, as well as guidelines for the storing of dangerous materials in containers.

3.3 *Fire prevention methods*

However, it is also necessary to ensure supervision of containers located in the storage yard in the container terminal. In this respect, the "Regulation of the Minister of Maritime Economy and Inland Navigation of 21 December 2016 on fire protection supervision in Polish maritime areas and sea ports and harbours" [10] as well as the "Regulation of the Minister of Foreign Trade and Maritime Economy of 24 February 1981 on fire protection in the area of sea ports and harbours" [11] provide the legal basis.

In Chapter 10 of the Fire Protection Regulation, we can read paragraphs devoted exclusively to the storage of containers and methods of preventing spontaneous combustion of cargo placed in them.

"§ 63.
1. Containers should be stored only on the premises of container bases or in designated storage yards.
2. Container bases and container storage yards should be equipped with fire hydrants, fire-fighting equipment and devices in accordance with applicable standards and with means of direct communication with the port fire brigade.
§ 64.
1. Container bases and container storage yards should be divided into quarters. The length of a quarter may not exceed 100 m, and the width - four times the width of the containers stored in a given quarter.
2. The permissible stacking of containers may amount to a maximum of 5 layers, except for containers loaded with easily flammable materials and refrigerated (air-conditioned) containers, which may be stacked to a height of 3 layers.
3. Stacking of containers loaded with class I hazardous materials and particularly hazardous materials of other classes is not permitted.
4. Fire routes of at least a width of 6 m, with a hardened surface.
§ 65.
1. Refrigerated (air-conditioned) containers with internal combustion engines and containers loaded with dangerous and explosive materials should be stored in designated quarters.
2. Refueling in the tanks of refrigerated (air-conditioned) containers may only be done from a tanker truck.
§ 66.
Container repairs may only be done in places designated for this purpose.
§ 67.
Container bases and container storage yards should be equipped with signs in Polish and English prohibiting smoking and the use of open fire. " [11]

4 OUTLINING THE PROBLEM – FIRE INCIDENTS IN SEAPORTS AND CONTAINER TERMINALS

4.1 *The scale of the fire problem in ports around the world*

All port logistics centers, not only in Poland, are exposed to the risk of accidents or fires during their daily work. Although today early fire warning systems are working better and better, detecting even the slightest temperature fluctuations, managers of container yards must be constantly on their guard. "The main fire hazard of a port results from the concentration of national assets of enormous value in a limited area, which consists of port infrastructure, materials, cargo, ships, industrial warehouses, equipment, installations, communication routes, etc. A similar degree of concentration of so many and so expensive investments and material goods does not occur anywhere else in the country, even in the largest industrial centers." [5]

The best example of an incident in a port was the recent fire in a hall on the premises of the hazardous waste incinerator in the Port of Gdańsk – the Port Service complex operating at the Northern Port, built in 1954. As we can read in an interview with the spokeswoman for Port Service, Ms. Anna Lewandowska, the workshop part caught fire, and as a result no hazardous goods were damaged, however, the fire brigades sent to extinguish the fire (22 sent, only 19 came on time) also ensured that there were no leaks of extinguishing agents into either the water or the air, which directly reduces the long-term impact of the fire on both the environment and the operation of the port.

Figure 3. Smoke over the Northern Port in Gdańsk, image source: own collection

4.2 *Consequences of fires*

"Sea ports, as economic facilities located at the interface between land and sea, are prepared in terms of technical and organizational aspects to handle foreign trade, by sea, together with means of sea and land transport. Therefore, ensuring an acceptable level of fire safety in ports must include within its scope all threats related to the characteristics of each of them. Although certain groups of fire threats are common to all types of ports, it would be necessary to differentiate the scale and effects of their impact depending on whether they concern commercial, passenger or military ports. Considering civilian ports, it should be borne in mind that especially those located in the agglomerations of Gdańsk-Gdynia or Szczecin-Świnoujście, are key elements for the national economy of our country. They also have the largest number and variety of threats. A separate category in terms of fire threats are fuel ports, such as the Northern Port in Gdańsk, where, due to the trade exclusively in media with specific fire characteristics - fire-hazardous materials, dedicated early detection and mitigation systems for this type of threat are used. " [5]

In addition to the danger to the port crew, it is also worth remembering:
- economic losses – damage or complete destruction of cargo, downtime in port operations, need to clarify the situation, control early warning and prevention systems, additional staff training,
- environmental losses – potential leaks of hazardous cargo into the atmosphere, negative impact on the natural environment as well as on people living in close proximity to the port (the best example is the ban on opening windows and leaving the house during and immediately after the fire extinguishing operation in the port of Gdańsk)
- logistical losses – the need to provide access during fire extinguishing operations, stop work at the terminal and find another place to store goods for a specified period of time, conduct an accident investigation.

There are incidents related to the dangers of storing cargo in containers all over the world. On August 12, 2015, in the port of Tianjin in North China, explosions occurred in a storage yard located in Binhai New Area, as a result of which 173 people died (including 104 firefighters taking part in the firefighting operation) and many others were injured. The explosions, with a power of about 800 tons of ammonium nitrate (equivalent to about 256 tons of dynamite sticks) occurred within about 30-40 seconds of each other. Although the cause of the incident was not known at first, after conducting an appropriate investigation, the cause of the explosion was found - incorrectly stored refrigerated container carrying nitrocellulose, as a result of which it overheated, and caused the harm.

4.3 *Difficulties in responding to fires in ports*

Despite increasingly modern early warning systems, incidents at ports involving fires continue to be a major challenge for container terminals.

Main reasons for the difficulties in responding:
- a vast area where containers are located,
- stacking of containers,
- delayed response of the services.

Due to the above, there is a growing need to find a modern way to early detect and warn of an approaching disaster, for example by using unmanned aerial vehicles – drones, equipped with appropriate devices that help in everyday work on the safety of container terminals and ensuring continuity of work.

5 FIRE PREVENTION SYSTEM

Taking into account the previous chapters, it is safe to point out an argument that it is necessary to develop new firefighting and fire preventing or detection systems. The last decade has brought rapid growth in the fields of automatics, autonomous or semi-autonomous vehicles, including unmanned aerial vehicles and Virtual-Reality (VR) or Augmented-Reality (AG) related technologies. This fact brings the opportunity to combine these ideas and try to create a fire prevention system based on them.

5.1 *Theoretical outline of the system*

Solution proposed in this paper include drones equipped with both normal and thermal cameras as well as the sensors to detect smoke, dustiness and fire-related pollution. To maintain high effectiveness, it is necessary to use some of the sensors directly in container stacks. VR could be an optional feature. The main characteristics of the system should be as follows:
- semi-autonomous - it should be possible to fix regular autonomous patrol path for the drones and to take manual control over them, when necessary,
- constant - the sensors mounted in containers stacks should maintain constant monitoring of basic parameters and the unmanned aerial vehicles should patrol specified area in regular intervals,
- three level alarm - entering each level should depends on the measurements taking by sensors,
- weather insensitivity - the system should take actual weather conditions into consideration when entering the next alarm level.

Every device should be connected to one server that performs analysis of the measurements and manages the states of the system.

As previously stated, the system should include three levels of actions:
- Normal mode - static sensors constantly monitor each parameter, drones patrol area autonomously on the fixed routes and taking additional measurements; the drones should fly in regular intervals; if every parameter fits in established requirements the report is generated.
- Pre-alarm mode - if one of the sensors detects abnormal parameters (e.g. temperature of a container higher than expected) the system should generate a warning. The nearest drone should be sent to the area that generates the warning and switch to manual control. Next, the properly trained worker should use the drone to check if the dangerous situation really occurs. Depending on the outcome the worker should turn off the pre-alarm mode or switch to alarm mode. In both cases the system should save logs from the incident and generate a report.

– Alarm mode - if multiple sensors detect abnormal parameters or one of the measurements indicate much higher temperature than expected or the worker starts the alarm mode manually or the system stays in the pre-alarm mode for too long it should enter the alarm mode. Nearest drones should be sent to monitor the situation and collect additional data. The information about the fire should be automatically sent to the fire station and to the terminal and port authorities. The zone exposed to the fire and the neighboring areas should be warned and evacuated. The system should collect all possible data, save logs and generate detailed report after the end of the alarm.

The general algorithm of the system is show in the chart below:

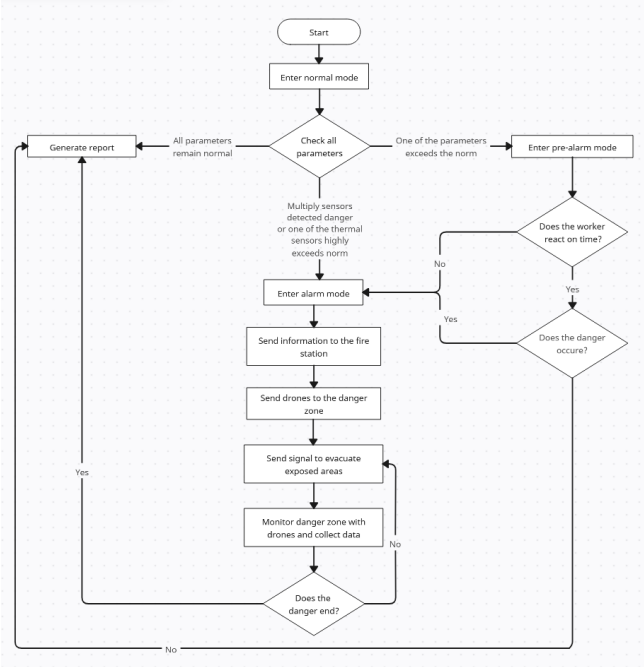

Figure 4. The algorithm of the system

5.2 *Issues*

The previous paragraphs provide a general description of the proposed system. However, there are some potential issues that have to be pointed out. In most of the world there are specified restrictions about operating a drone. The law in Poland provides different types of licenses, divided in two categories - open and special. The specification of the described system would require the special license. In consequence, the process of training the worker to operate a drone would be more difficult and expensive and obtaining appropriate consents to perform described actions would be more complicated. Restrictions directly related to the operation of aerial vehicle in the port area may also pose a problem.

Another difficult case is to set the optimal places for sensors to maintain effective measurement of the scoped parameters. The devices must not influence the normal workflow on the terminal and simultaneously they have to collect enough data to provide constant and proper monitoring of the container stack.

The process of practical development of the described system should also cover the way of exchanging and storing the data. There are many ways to do it and every solution has some advantages and disadvantages. The optimal method depends on the device selection, planned budget and the detailed design assumptions.

The described system will collect a large amount of data. The information gathered from the sensors won't be directly connected to the particular cargo. However, it could provide many details about the inner working process at the terminal, the dangerous incidents and the methods of handling them. Taking into consideration the geopolitical situation of Poland and the growing possibility of escalation of the war fought directly abroad, as well as the fact that our country is involved in this conflict in the socio-economical way it is crucial to maintain high standards of cyber security. Although it is difficult to predict the specific usefulness of the information gathered by the described system, it could potentially be utilized in some sort of sabotage or similar military actions. It is necessary to define strict terms of gaining access to the data and to ensure safety.

5.3 *Possible improvements and prospects*

The system proposed in this article is originally designed for operation in container terminals, particularly in Poland. However, if the solution proves effective it could be implemented on other types of terminals with minor changes.

The system itself could also be improved by expanding the patrol paths of the drones and expanding the devices by mounting additional dust sensors on them. This solution could be especially useful in the mass terminals, where it could examine the level of dustiness at particular distances from the terminal.

In the future the system could be expanded to collect and process even more types of data, which could be useful in statistical analyses, research related to the environment and planning the seaports areas.

6 CONCLUSION

The main goal of this paper is to propose an innovative fire prevention system that could be implemented in the container terminals. The previous paragraphs contain descriptions of the particular functions of this system as well as the exemplary algorithm of work. Both the issues and prospects were mentioned. Further research is necessary and this paper stands as an introduction to the practical development of the system described in the article.

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