System for Estimation of Danger Zones and Safe Evacuation Routes in the Face of Bomb Threat - Discussion on the Approach

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***Abstract*—Anti-terrorist measures taken by the police are among the most dangerous operations of the uniformed services, both in the country and beyond its borders. Trained police officers, during their duties, risk their health and lives in order to protect the citizens and their property. During an anti-terrorist operation many external factors encountered in a scene may increase assault squad's safety and thus also affect the ultimate success of the operation. However, these factors are not always exactly known and, therefore, not taken into consideration during the planning process. One of these factors is the location of the performed action. In order to efficiently eliminate the risk, officers have to know the exact placement of a suspicious object (potential explosives) and be familiar with all features of the environment that may affect ongoing operations, such as building layout, terrain, etc. In such case, it is possible to determine safety zones and evacuation routes for the outsiders.**

In the absence of time, even more important factor is the planning duration. Most of the anti-terrorist operations require a swift response to the arising threat. Despite having even the most detailed information about the operation's location, there is often no time to take full advantage of this knowledge. Therefore every second, which can be saved on action planning, might become invaluable later on. After all, the ultimate success of the operation is often dependent on its speed.

***Index Terms*—destruction field, explosives, shock wave, simulations.**

I. Introduction

In the era of dynamic events in the world, the most common terrorist threats are certainly all kinds of explosives that can be placed nearly anywhere.

Currently obtaining the explosives that can be used to build a bomb has become much easier. This concerns both, the explosives of military origin, mining explosives or so called "rusty death" – so generally the materials recovered from the remains of the armed conflicts or used in industry, and Home Made Explosives (HME) [1].

Technical possibilities to construct an explosive material are enormous. The only limitation for the designer in this field is his imagination. For this reason, preventing the terrorist threat, such as mentioned explosives, cannot be covered by any strict standards. Each one of such a threat should be treated individually, without trying to classify it into the existing emergency protocols.

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Currently it is not feasible to predict all possible scenarios. Moreover, this situation severely reduces possibilities of predicting what might happen to the surroundings of the explosives location, what would be destroyed first, or would there occur any secondary explosions, etc. Additionally, taking into account the possibility of enriching the bombs with nails, screws or other similar elements, predicting the impact in the traditional way is nearly impossible.

Aim of the authors is to highlight the need for developing methods for modeling of the danger zones in the area of the bomb threat and algorithms for calculating and optimizing safe evacuation routes. Determining these zones would accelerate and ensure the whole decision-making process in the planning of anti-terrorist operations.

II. The Current Reality

Currently, when the bomb threat occurs the special group of sappers is dispatched to that place. They are responsible for taking any actions necessary to eliminate the threat and protect citizens and their property.

The first task of arrived sappers is to assess the level of potential danger. This is done on basis of the situation found on the spot and data acquired form the quick reconnaissance.

However, the officers are not always able to immediately identify what they are dealing with. An explosive device may, for example, be placed in opaque wrapping, what makes it highly risky to open the package in order to see what is inside. Mentioned reconnaissance can be really helpful at this point, as it allows sappers to get the minimum knowledge about the suspicious package: when exactly it was noticed, where was it placed, what is the purpose of that location, was it already reported, etc.

Another important factors are undoubtedly experience and knowledge that officers gained through the years of service. That, together with specialized equipment and information gained at the spot gives sappers a good basis to assume what materials they are dealing with and thus what steps should be taken to neutralize it. At the same time, using this information, they can determine the level of the threat and try to predict effects of the potential detonation of explosives.

Unfortunately due to the fact that decision-making is influenced by a lot of factors all scenarios that may occur as a result of the explosion are unpredictable.

III. Methods of Achieving the Goal

The explosion phenomena, according to experts, is defined as a physical or chemical process of a very fast transformation of the system, which is accompanied by a change of potential energy into mechanical energy [2]. A characteristic feature of the explosion is a sharp increase in pressure in the vicinity of the blast – a wave of elevated pressure (also called the shock wave). This is the main cause of destructive action of the explosion.

Depending on the speed of propagation of the elevated pressure wave, three types of explosion can be distinguished:

- deflagration (the main explosion) - wave velocity < 400 m/s,
- explosion - wave velocity > 400 m/s, but less than the maximum,
- detonation - wave velocity (of detonation) maximum for a particular explosive material under given circumstances, preserving the condition of > 400 m/s.

These definitions are used in the sapper nomenclature, where the value of 400 m/s is used as a standard of the shock wave propagation.

An explosive may deflagrate, detonate or explode, depending on its conformation, weight, moisture, content of the dopants and the density, as well as external conditions, such as: humidity, atmospheric pressure, temperature and size of the adjacent space. The formation of the shock wave is strongly determined by above-mentioned factors. In addition, the placement of explosive charge in a particular location, e.g. at a pillar or on a wall of the building, in the central part of the empty room, will differently affect the shape the wave. It should also be considered what happens when the explosive device changes its location, e.g. while it is moved into a safe place. Possible explosion, after changing its location (e.g. raising it), may cause more damage than if the device was moved close to the ground.

As indicated above, there are many factors that determine the behavior of the shock wave. If, however, one we will be able to acquire them all, or at least the vast majority of them, modeling of the shock wave's impact will reflect the real situation more accurately [3].

Model of the shockwave's influence on surroundings should include the basic parameters defining the mechanical impact. These include:

- maximum positive pressure of the shockwave

$$\Delta p^{+} = p^{+} - p_0 \tag{1}$$

- maximum negative pressure of the shockwave

$$\Delta p^{-} = p_0 - p^{-} \tag{2}$$

- duration of the positive pulse phase

$$\mathcal{T}^{+} \tag{3}$$

- duration of the negative pulse phase

$$\mathcal{T}^{-} \tag{4}$$

The above values and their dependencies are illustrated in the graph below in Fig. 1.

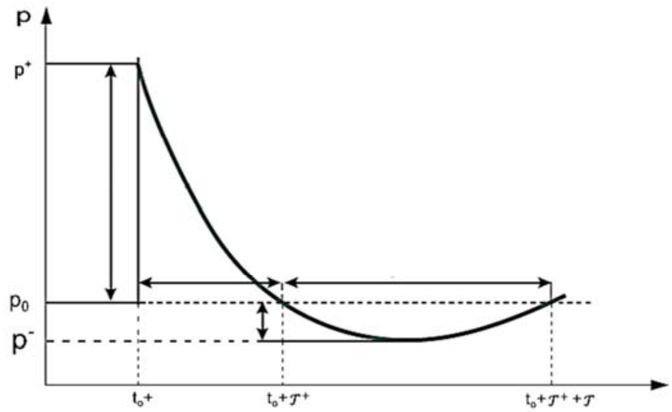

Fig. 1. The pressure change in time [4].

Additional features of the shockwave are its positive and negative pressure pulses, which are time integrals of the positive and negative pressure:

$$I^{+} = \int_{t_0}^{t_0+\mathcal{T}^{+}} [P(t) - p_0] dt \tag{5}$$

$$I^{-} = \int_{t_0+\mathcal{T}^{+}}^{t_0+\mathcal{T}^{+}+\mathcal{T}^{-}} [p_0 - P(t)] dt \tag{6}$$

While modeling the propagation of the shockwave, its velocity together with density and temperature of the gaseous products of the explosion should be taken into consideration. These parameters have a significant impact on the aforementioned values.

Destructive effect of the shockwave is caused by its positive pressure and positive pressure pulse. Exposure to the shockwave changes the distribution of stresses in the real system's structure. Duration of the shockwave and its positive pressure lead to varying degrees of deviations from equilibrium of the system or generates its deformation. It is possible to set maximum allowable deflection from the equilibrium position relative to exerted energy. Exceeding this limit causes breakdown of the system.

Having such data it is possible to determine the zones of direct ("A"), indirect ("B") and distant ("C") danger, as well as their range of destruction (Rc – radius of zone "C", Rb - radius of zone "B", Ra - radius of zone "A") as shown in Fig. 2.

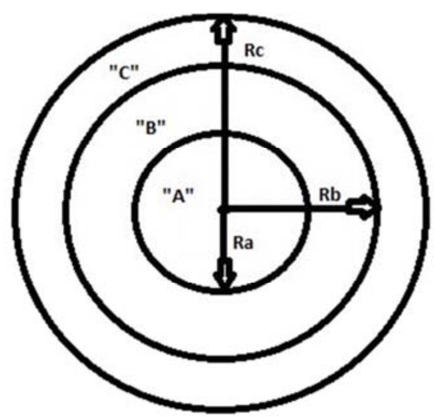

Fig. 2. Danger zones.

Before attempting to determine these zones, area of the shockwave should be divided also into 3 zones [5, 6]:

a) direct explosion zone ($\lambda < 1$),

b) indirect explosion zone ($1 < \lambda < 10$),

c) distant explosion zone ($\lambda > 10$).

According to the Sachs's law, dimensional positive pressure p_s and positive pressure pulse I_s are functions of dimensionless distance λ:

$$\lambda = \frac{r \cdot p_0^{\frac{1}{3}}}{E^{\frac{1}{3}}} \tag{7}$$

$$I_s = \frac{I^+ \cdot C_o}{E^{\frac{1}{3}} \cdot p_0^{\frac{2}{3}}} \tag{8}$$

where:

r – distance from the center of the explosion,

p_0 – initial pressure in the environment,

C_o – velocity of sound.

In the literature one can find the concept of relative distance. It is called the reduced distance [symbol] and allows to compare values of pressure for different explosive materials masses at varying distances [7]:

$$\overline{R} = \frac{r}{m^{\frac{1}{3}}} \tag{9}$$

where:

r – distance from the center of the explosion in meters,

m – mass of explosive material in kilograms.

Mentioned Sachs's law does not apply to the direct zone of the explosion, since the distances are close to the size of the explosive material ($\lambda < 1$). Shape and initiation point affect movement of the shockwave. For other areas (indirect and distant) empirical and asymptotic formulas are used, which allow the calculation of pressure at the head of the shockwave:

$$\begin{aligned} \Delta p^+ &= 1{,}38\overline{R}^{-1} + 0{,}543\overline{R}^{-2} - 0{,}0035\overline{R}^{-3} \quad \text{for} \quad 0{,}05 \le \overline{R} \ll 0{,}3\, m/kg^{\frac{1}{3}} \\ \Delta p^+ &= 0{,}607\overline{R}^{-1} + 0{,}032\overline{R}^{-2} - 0{,}209\overline{R}^{-3} \quad \text{for} \quad 0{,}3 \le \overline{R} \ll 1{,}0\, m/kg^{\frac{1}{3}} \\ \Delta p^+ &= 0{,}065\overline{R}^{-1} + 0{,}397\overline{R}^{-2} - 0{,}322\overline{R}^{-3} \quad \text{for} \quad 1{,}0 \le \overline{R} \ll 10{,}0\, m/kg^{\frac{1}{3}} \end{aligned} \tag{10}$$

where:

Δp^+ – maximum positive pressure in MPa,

$\overline{R}$ – reduced distance in $m/kg^{\frac{1}{3}}$

The above formulas are used, when the explosive is placed in the air (e.g. hanged). In cases, where explosive is positioned on a surface, such as ground or concrete, the weight of the material used for the calculation should be doubled [8].

In the literature there are also formulas proposed by Henrych:

$$\begin{aligned} \Delta p^+ &= 14{,}0717\overline{R}^{-1} + 5{,}5397\overline{R}^{-2} - 0{,}03572\overline{R}^{-3} + 0{,}00625\overline{R}^{-4} \quad \text{for} \quad 0{,}05 \le \overline{R} \ll 0{,}3\, m/kg^{\frac{1}{3}} \\ \Delta p^+ &= 6{,}1938\overline{R}^{-1} - 0{,}3262\overline{R}^{-2} + 2{,}1324\overline{R}^{-3} \quad \text{for} \quad 0{,}3 \le \overline{R} \ll 1{,}0\, m/kg^{\frac{1}{3}} \\ \Delta p^+ &= 0{,}662\overline{R}^{-1} + 4{,}05\overline{R}^{-2} - 0{,}322\overline{R}^{-3} \quad \text{for} \quad 1{,}0 \le \overline{R} \ll 10{,}0\, m/kg^{\frac{1}{3}} \end{aligned} \tag{11}$$

and Sadowski:

$$\Delta p^+ = 0{,}754\overline{R}^{-1} + 2{,}457\overline{R}^{-2} + 6{,}5\overline{R}^{-3} \quad \text{for} \quad 1{,}0 \le \overline{R} \ll 10{,}0\, m/kg^{\frac{1}{3}} \tag{12}$$

Above formulas, applied to the explosive placed in the air, Sadowski (13) and Henrych (14) formulas should be used when calculating the second characteristic value of the shockwave – the positive pressure pulse:

$$\begin{aligned} \frac{I^+}{m^{\frac{1}{3}}} &= 350\overline{R}^{-1} \quad \text{for } \overline{R} \ge 0{,}5 \\ \frac{I^+}{m^{\frac{1}{3}}} &= 150\overline{R}^{-1} \quad \text{for } \overline{R} \ge 0{,}25 \end{aligned} \tag{13}$$

$$\begin{aligned} \frac{I^+}{m^{\frac{1}{3}}} &= 660 - 11150\overline{R}^{-1} + 6290\overline{R}^{-2} - 1004 \quad \text{for } \overline{R} \in [0{,}4;\ 0{,}75] \\ \frac{I^+}{m^{\frac{1}{3}}} &= -322 + 2110\overline{R}^{-1} - 2160\overline{R}^{-2} + 801\overline{R}^{-3} \quad \text{for } \overline{R} \in [0{,}74;\ 3] \end{aligned} \tag{14}$$

where:

I^+ – positive pressure pulse in Pa·s,

m – mass of the explosive material in kilograms,

$\overline{R}$ – reduced distance in $m/kg^{\frac{1}{3}}$.

Knowing these values, together with the potential temperature emitted during the explosion, it is possible to simulate the propagation of these phenomena in a given environment, and hence, the effects they cause, such as damaging structures of the building as shown in Fig. 3.

In order to achieve the intended effects, it is necessary to conduct a series of tests and experiments that require to combine the knowledge of experts in many fields such as: computer technology - phenomena modeling, constructions, materials engineering and crisis management.

Using artificial intelligence methods, such as neural networks, together with expert systems, it is possible to classify the identified explosive materials to groups that are already known, and thus also possible to estimate their destructive power. Use of the numerical methods gives the opportunity to simulate the process of the explosion, as well as its detonation products' impact on the elements in the adjacent environment [9].

The above solutions, used in conjunction with algorithms for paths calculating, will make it possible to determine the safe evacuation routes in case of a bomb threat.

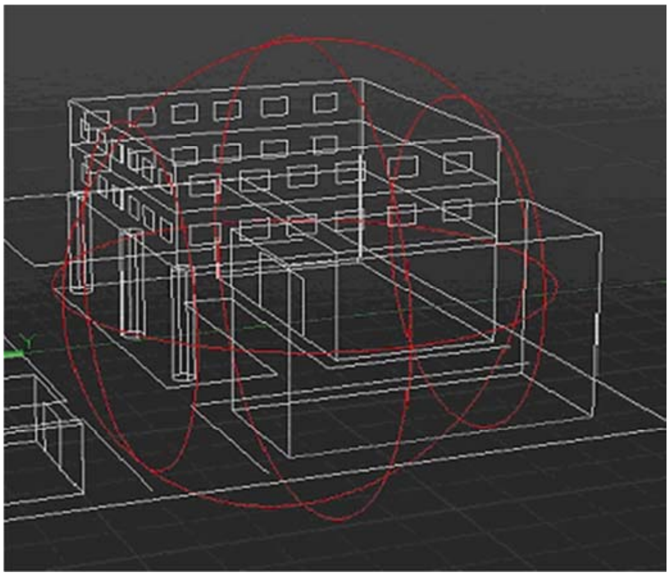

Fig. 3. Simulation of the destruction zone as a result of an explosion.

IV. Proposed Technical Solution

The intention of the authors is to develop a computer software that will support the work of the sappers. The main functionality of the proposed solution will simulate the behavior of the explosive material during its detonation under certain conditions, as well as the impact of the shock wave on the adjacent environment.

Considering the fact that not every sapper using such software is a skilled computer specialist, the task of the authors is to simplify the interface so as to minimize the amount of data required to enter by the operator. At the same time, it is not intended to limit the amount of necessary data.

The use of web technology will allow the system to automatically download digital maps of the environment from the server. Through the use of advanced visualization methods based on 3D libraries, it will be possible to transform the obtained spatial data, and present it in the three-dimensional form. Such an approach eliminates the necessity for manual "drawing" the area covering the operation.

Thanks to modern X-ray capable of determining weight and density of the explosives, it is possible to obtain the necessary information about the threat. Additional information can also be obtained from the vapor analyzer.

The acquired data can be automatically included in the described software and, thanks to the use of artificial intelligence methods mentioned above, allow to classify the material into the appropriate type. Thus, the relevant information about the explosives can be obtained, including: detonation velocity, sensitivity coefficient and others.

Helpful information will also be provided by data on atmospheric conditions that prevail at a given location. That includes: ambient temperature, humidity and ambient atmospheric pressure. This data should, wherever possible, be dynamically and automatically provided using the appropriate sensors.

Due to the fact that the explosive charge can be placed in inaccessible locations, its positioning in the modeled environment may become problematic. The proposed solution is to use a GPS locator that can be placed at the explosive using a mobile robot or drone. This eliminates the need for a personal approach of the officer and, thereby, increases his safety. Having the above data the software will be able to graphically represent the formation of a shock wave in a given environment, also rendering the reactions occurring when the wave front collides with encountered objects. The Fig. 4 illustrates described solution and Fig. 5 illustrates diagram of the simulator algorithm:

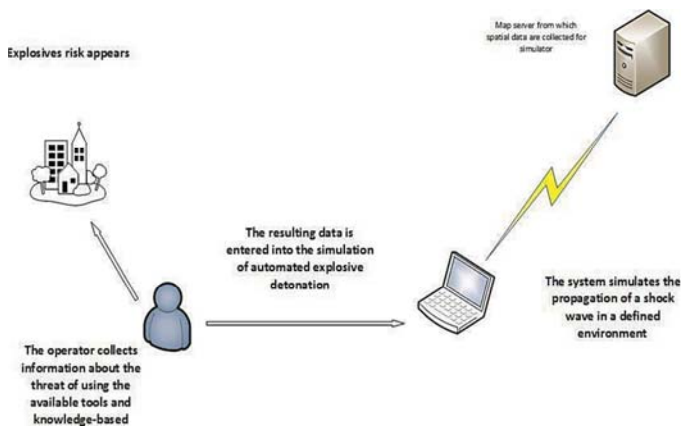

Fig. 4. System design.

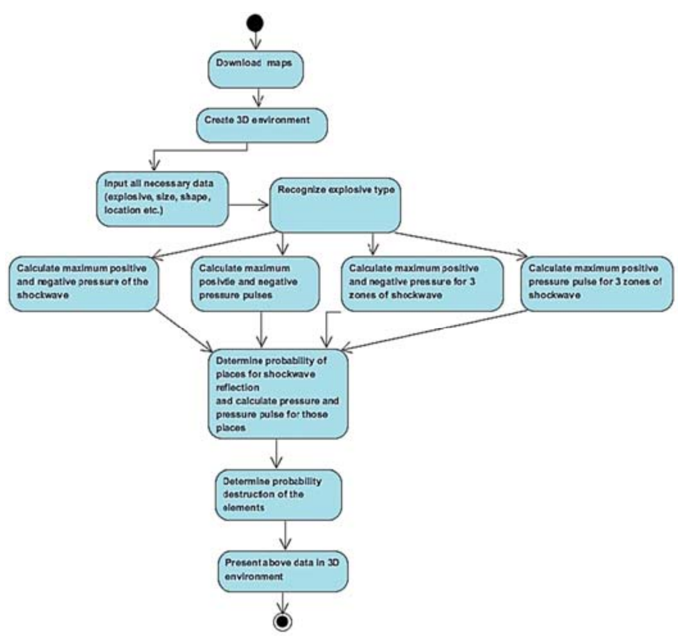

Fig. 5. Block diagram of the simulator algorithm.

Expertise in the field of explosives and strength of materials implemented in the system will allow the modeling and simulation of all the possible scenarios of an explosive detonation and the impact of the shock wave on the environment. With this approach, sappers will be able to select the appropriate treatment protocol, safest for both them and the environment. Furthermore, the proposed software will accelerate the decision-making process itself.

V. Conclusion

Currently Polish police do not use solutions that enable modeling and simulate activities of anti-terrorist units. Using the technical potential together with the knowledge and experience of experts gives the possibility to develop a computer simulation system allowing to predict different scenarios, which so far have not been taken into consideration during police operations.

3D modeling of urbanized environment including all of its physical properties as well as the characteristics of explosives provides the results reflecting the actual process in detail. Using such a system gives the opportunity to take the appropriate steps and minimize the risk of anti-terrorist operation.

Described solution is highly applicable, not only for current police activities. Such system could be successfully utilized by other services like military, fire department or the Government Protection Bureau. Additionally it can be used to determine the weak points of critical infrastructure objects, which are important to the national defense and interests of the state.

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