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DEVISING A METHOD TO ADAPTIVELY DETERMINE HUMAN MOVEMENT SPEED IN CROWD BEHAVIOR SIMULATION AT EXTREME EVENTS

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The subject of this study is the dynamics of human flow at extreme events, which are modeled using a computer simulation model.

The task addressed relates to the insufficient accuracy in determining human speed with existing approaches when modeling crowd behavior at extreme events. Specifically, the desired walking speed of a person is set fixed or discretely, which can lead to significant errors as it does not correspond to real-world conditions. Models based on pre-collected data compromise accuracy under different conditions.

A method is proposed to adaptively determine human movement speed at extreme events, which takes into account individual spatial constraints and the narrowing of the effective field of view under stress. Simulation modeling has shown that the method devised significantly improves the accuracy of the models. The average modeling error decreased from 28.05 % to 12.06 % for a circular profile of human projection, and from 31.5 % to 6.09 % for an elliptical profile.

The results are explained by the individual consideration of local crowd density, realistic narrowing of the field of view within the range of 30° to 0.5°, and corresponding adaptive adjustment of the desired speed.

A feature of the devised method is its universality as it does not depend on a specific scenario or pre-collected empirical data. The method is based on general patterns of human interaction with the environment and is therefore suitable for use even in cases where field studies are impossible or difficult.

Provided that two-dimensional models are used, the proposed method could be applied to simulate crowd behavior in automated crowd management systems, software packages for assessing the safety of mass events, and designing evacuation routes

Keywords: adaptation, speed, modeling, crowd, density, behavior, vision, evacuation, management, safety

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1. Introduction

Studies of human flows have been developing over the past decades and remain highly relevant in the current context. Challenges, including spontaneous mass rallies, protests, terrorist acts, and military actions, which are accompanied by large crowds of people in places where such phenomena have not been observed before, require a rethinking of conventional approaches to the analysis of crowd behavior.

Several large-scale terrorist attacks have been observed in Europe [1], which caused significant casualties and the destruction of critical infrastructure in cities such as Brussels, Paris, Madrid, and London. Along with this, there is an increase in the number of illegal border crossings by crowds of migrants, which adds to the complexity of security issues. Similar extreme conditions arise during military attacks when citizens are forced to seek bomb shelters, which is often accompanied by mass panic [2]. These cases highlight the need for a detailed study of crowd behavior at extreme events and for devising effective methods for predicting the dynamics of human flows. That is why researchers are increasingly using simulation models that allow them to reproduce the dynamics of human flows [3, 4]. Therefore, conducting research aimed at improving the accuracy of existing models seems to be very relevant.

2. Literature review and problem statement

Paper [3] reports the results of the first experimental studies on real human flows, which had different scales and covered different categories of people. It is noted that the density of the crowd varies widely depending on the situation. Under normal conditions, the density is low, the movement is orderly. Under extreme conditions – under the influence of a sudden increase in psycho-emotional tension – panic often occurs. In such cases, the density of the crowd increases sharply, which leads to traffic jams, blocking of evacuation exits, and an increased risk of injury. It is noted that with an increase in the density of the crowd, its speed decreases due to the limitation of free space. However, obtaining new data on the behavior of the crowd in each specific situation exclusively empirically remains a very difficult task due to the large time, financial, and organizational costs. A likely option to overcome these difficulties is the use of simulation modeling. It is noted that a key element of these models is the approach to determining the speed of a person in a crowd, which depends on the interaction with surrounding barriers.

In work [5] that considers the development of multi-agent models the speed of a person is determined based on four predefined fixed options for the size of the personal space. In turn, this space is determined depending on the flow density in a predefined radius around the person. However, this approach is too simplified and deterministic, which can cause significant errors due to a rough approximation of actual conditions.

An alternative approach aimed at eliminating discreteness in determining speed is implemented within the framework of psychophysiological interaction models [6]. In these models, the speed of a person's movement is determined taking into account his/her purposefulness, as well as the influence of external environmental factors. Interaction with obstacles is described by repulsive forces, the magnitude of which increases exponentially with decreasing distance to the object, which makes it possible to reproduce the inherent human tendency to avoid potential barriers that can complicate movement. At the same time, the desired speed of movement, which is included in the equations, is most often given as a constant value that corresponds to the maximum possible speed of a person. This approach does not take into account individual and situational fluctuations in the desired speed that may arise under the influence of local conditions. Despite the significant number of models built, the problem of accurate identification of parameters that determine behavior in a crowd remains open. Their incorrect determination for a specific scenario can lead to significant modeling errors. The main reason for this uncertainty is the difficulty of conducting experimental studies under real extreme conditions, which significantly limits the ability to collect reliable empirical data.

In works [7, 8], it is proposed to solve the problem of determining the parameters of psychophysiological interaction using deep learning methods. The neural network dynamically determines the key parameters of the model, such as the desired speed and repulsion force, depending on the current human environment. This approach increases the accuracy of the modeling but does not guarantee generalization to scenarios for which data were not presented during the training of the neural network. In addition, there is a problem of interpretability of the results in cases where the simulated human behavior unexpectedly differs from the actual one. The reason is the fundamental opacity of deep learning methods.

Another approach based on the use of empirical data of movement to determine speed is reported in [9]. Within its framework, it is proposed to use artificially constructed functionals to determine the speed of a person, which determine the similarity to real data of the local environment in which the person is located. This approach makes it possible to significantly bring the model closer to actual conditions; however, its effectiveness largely depends on the quality and completeness of empirical data obtained in specific situations. The presence of incomplete or low-quality data can lead to a significant decrease in the accuracy of modeling. A model trained on data from one specific area or scenario may inadequately reflect the behavior of the crowd in other situations. Accordingly, the main problem of this approach is its lack of universality. This issue remains unresolved due to the need to collect and standardize a large amount of empirical data obtained under various conditions and scenarios. The objective difficulties of conducting such studies are significant financial and time costs for performing large-scale full-scale experiments.

It should also be noted that an important factor affecting the determination of the speed of a person's movement is the spatial nature of the consideration of obstacles. In [10] it is noted that in most modern models the influence of the environment is considered comprehensively – that is, from all sides around the person. Despite the prevalence of such an approach, it contradicts the features of real human perception. In reality, a person reacts mainly to objects that are within his/her field of vision. Although such a simplification is due to an attempt to simplify calculations within the framework of simulation modeling, it can lead to a significant decrease in the accuracy of the results.

A likely option to overcome this drawback is models in which the impact of obstacles on a person in the flow is limited to a certain observation sector. In particular, in [11] it is proposed to use a sector with a width of 170°. However, in stressful situations, a person's field of view can significantly narrow due to the so-called "tunnel vision" effect, which causes a loss of the ability to perceive information from peripheral zones. Taking this effect into account is important for building models that can accurately reproduce real human behavior at extreme events.

All this gives grounds to argue that it is advisable to conduct a study aimed at solving the problem of insufficient accuracy in determining a person's speed in existing approaches to modeling crowd behavior at extreme events.

3. The aim and objectives of the study

The purpose of this study is to devise a method to adaptively determine human movement speed at extreme events, which could improve the accuracy of crowd behavior modeling.

To achieve the goal, the following tasks were set:

– to determine the angle from the center of vision that determines the field of view of a person in an extreme situation;

– to determine the local density of the crowd depending on the horizontal profile of the person's projection (circle, ellipse);

– to establish the dependence of human speed on crowd density;

– to define a sequence of steps for implementing the method for adaptive determination of human movement speed at extreme events;

– to perform software implementation and testing of the devised method.

4. The study materials and methods

The object of this study is the dynamics of human flow at extreme events, modeled by using a simulation computer model.

The subject of the study is the process of adaptive determination of the speed of human movement at extreme events, caused by local spatial constraints and narrowing of the field of view under the influence of stress.

The main hypothesis of the study assumes that the desired speed of human movement under extreme conditions does not always remain the maximum possible. The study suggests that speed regulation is due to the action of the instinct of self-preservation. During movement, a person, in order to avoid the potential risk of falling or colliding with an obstacle, constantly adapts his/her desired speed to a specific situation. The key factor in such adaptation is the size of the personal space in the field of view of a person and its occupancy, which can be determined during modeling through the local density of the crowd.

Additionally, the study assumes a significant reduction in the effective field of view of a person at extreme events. Under such conditions, the phenomenon of "tunnel vision" is observed, when a person's attention is concentrated exclusively on a narrow central zone of perception.

This study takes into account the results of a large-scale series of field experiments reported in [3], which were aimed at establishing the relationship between the speed of movement of people and the density of the crowd. Based on these empirical data, it is assumed that, knowing the local density of the crowd at each point in space, it is possible to determine the real desired speed of an individual person since it directly depends on local spatial constraints.

To achieve the goal of the study, a combination of analytical, functional-approximation, and simulation research methods is used, which provide both conceptual clarity and mathematical formalization of the results.

The analytical method is used in the work to determine the local density of the crowd depending on the geometric parameters of the horizontal projections of people (circle or ellipse), which makes it possible to quantitatively assess individual spatial constraints. The choice of the analytical approach is due to its accuracy and the possibility of physical interpretation of the results obtained.

The functional-approximation method is used during the study to approximate empirical data since it provides sufficient accuracy and stability of numerical solutions and also has a clear statistical justification.

Simulation modeling was chosen due to the complexity of conducting full-scale experiments at actual extreme events. Within the framework of this study, crowd modeling is limited to considering an exclusively two-dimensional approach based on a psychophysiological description of human interaction. The geometric profile of a person is considered as a circle or ellipse, which corresponds to the most common scientific practices in the field of crowd modeling. It is also assumed that all participants in the crowd have the same mass and wear the same clothes.

Since the existing software for simulation modeling of crowd movement did not provide sufficient flexibility to adjust the basic behavioral models [12], for the purposes of this study I have independently developed a specialized software package (Fig. 1). It implements a psychophysiological model of interaction and makes it possible to take into account individual changes in the desired speed depending on local spatial constraints and the characteristics of human perception of the surrounding space under extreme conditions.

The initial data for modeling is the room layout, represented as a set of segments corresponding to the walls. On the plan, the crowd zone is defined by a rectangular area, within which the software package forms the initial distribution of people according to the principle of hexagonal packing, adapted to the given crowd density. In this case, not only the geometric shape of the person's projection, which is modeled as a circle or ellipse, but also the seasonality of clothing, which affects the size of the projection, is taken into account.

The direction of movement of the crowd is determined by specifying the coordinates of the target point, which ensures integrated consideration of the desired trajectory in the model.

The simulation modeling is performed using hardware, which includes a computer with an Intel Core i7-4770 processor (3.4 GHz), 64 GB of RAM, and an NVIDIA graphics card with 2 GB of video memory.

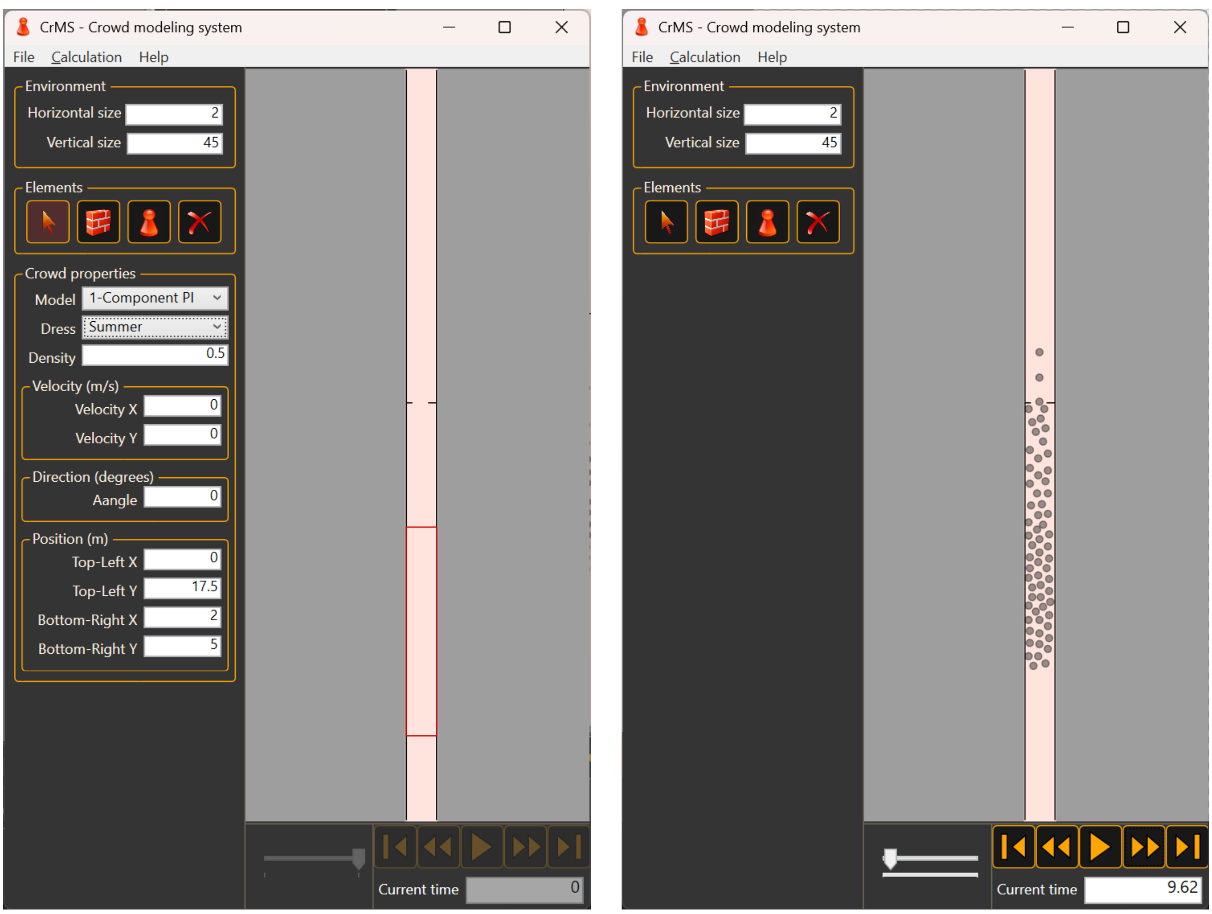


Fig. 1. Specialized software package for crowd behavior simulation

5. Results of the study to adaptively determine human movement speed under extreme conditions

5. 1. Narrowing of the visual field at extreme events

The human field of vision covers a significant part of the surrounding space [13]. Under normal conditions, the monocular (one-eye) horizontal field of vision extends to approximately 60° towards the nose (nasally) and to 100–110° towards the temple (laterally). The vertical field of vision covers about 70–80° (up and down relative to direct gaze). Due to the overlap of the fields of the two eyes, the total binocular field of vision covers about 160° horizontally. Within this space, the central and peripheral zones are distinguished. The central zone is provided by the macula (Fig. 2), which is responsible for the highest resolution and covers an area up to 18° from the center of vision, while the periphery is responsible for orientation and detection of movement (Fig. 3).

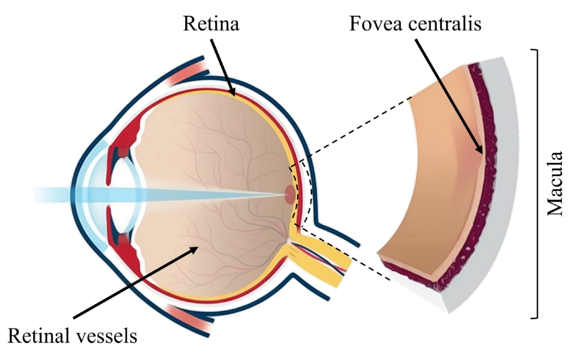


Fig. 2. The structure of the human eye

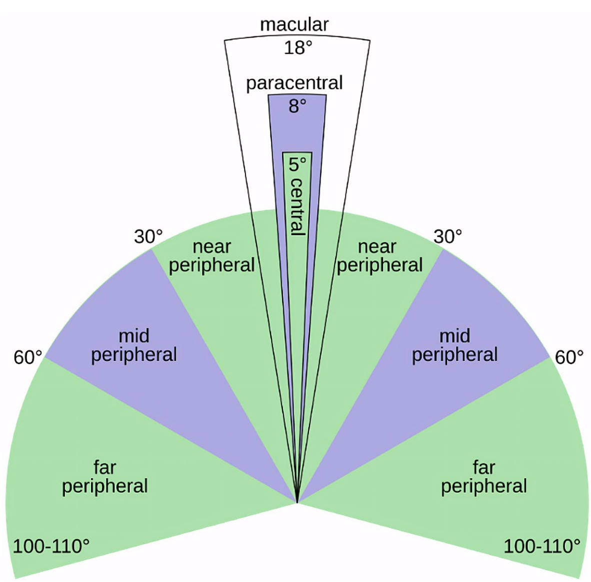


Fig. 3. Human field of vision [13]

Under the influence of extreme stress or panic, a temporary narrowing of the effective field of vision occurs, known as tunnel vision [13]. This effect is due to both physiological and neurocognitive changes. Activation of the sympathetic nervous system is accompanied by the release of adrenaline, which causes the pupils to dilate and the slowing or complete cessation of saccades – rapid, involuntary eye movements that help focus light on the fovea (central pit) [14]. As a result, the brain recalibrates perception, focusing attention on the central area, where the image is most detailed, and information from the periphery is suppressed. Thus, the scientific definition of tunnel vision during stress combines two aspects: physiological narrowing (due to changes in the work of the eye and sensory pathways) and cognitive narrowing (due to the redistribution of attention). Both factors ultimately result in a panicked person effectively seeing only a limited central portion of their normal field of vision, as if looking through a tunnel or narrow tube.

Empirical evidence, both from studies of drivers and pilots and from the testimony of law enforcement officers, indicates a significant narrowing of the field of vision under stress. For example, when driving at speeds of up to 130 km/h, drivers' effective viewing angle can decrease to 30°, which is analogous to tunnel vision caused by the need to focus on the road [15]. In situations of extreme threat, the field of vision is even more significantly narrowed. According to observations in law enforcement agencies [16], more than half of officers involved in armed incidents reported tunnel vision during the incident. Case analysis reveals that in many gunfights, the officer lost up to 75 % of his/her peripheral vision – effectively reducing his/her field of vision to a quarter of its normal size.

It is important to note that the effects of stress can vary depending on its intensity, duration, and individual characteristics. Studies among military, sports shooters, and pilots show that moderate levels of stress narrow the effective field of view to 30°, and under conditions of extreme nervous tension it can narrow to approximately 0.5° [17].

Thus, the analysis of neurophysiological mechanisms and empirical data reveals that under the influence of stressful situations, a person develops tunnel vision, which is characterized by a significant narrowing of the effective field of view. The degree of this narrowing depends on individual characteristics and can range from approximately 30° under moderate stress to 0.5° under conditions of extremely high psycho-emotional stress. In order to more accurately reproduce actual conditions during simulation modeling, it is advisable to assign in advance to each person in the human flow an individual limiting angle of the effective field of view in the range from 0.5° to 30°.

5. 2. Local crowd density

There are several approaches to quantifying the density of a crowd of people [3, 4]. One of the most common is to define crowd density as the ratio of the number of people to the area they occupy (people/m^2):

$$D = \frac{N}{wl}, \tag{1}$$

where N is the number of people in the flow; w is the width of the flow; l is the length of the flow.

An alternative definition is also used, according to which the crowd density is calculated by dividing the total area of the horizontal projections of people by the area of the zone of their placement (m^2/m^2):

$$D = \frac{\sum S}{wl}, \tag{2}$$

where S is the area of the horizontal projections of each person in the flow.

Another option for determining is the approach in which the density is calculated through the area per person (m^2/person):

$$D = \frac{wl}{N}. \tag{3}$$

It should be noted that expressions (1) and (3) most accurately describe the cases of homogeneous flows, for example, when all participants are approximately the same height and have a similar amount of clothing (summer or winter). At the same time, formula (3) can theoretically be applied to heterogeneous flows under certain assumptions.

Practical observations show that the density of the flow is not constant in length or width and can dynamically change over time. Therefore, for each participant in the flow, depending on the people and obstacles around, it is advisable to consider the local density of the crowd. It is on it that the speed of movement of a particular person directly depends since with an increase in local density, the possibilities for maneuver and freedom of movement decrease.

In view of the above, it is proposed to determine the local density of the crowd D for a particular person in the crowd as the ratio of the area of its horizontal projection f to the area of personal space F, limited by the shortest distance to the nearest person or obstacle:

$$D = \frac{f}{F}. \tag{4}$$

Several approaches can be used to calculate the area of a person's personal space in a crowd. The most common is the Voronoi diagram method [18], which is widely used for analyzing spatial structures, in particular in crowd research. This approach involves dividing the space into cells so that each point inside a certain cell is closer to a given point (for example, the center of mass of a person) than to any other. The area of such a cell is considered the personal space of the corresponding person. This method makes it possible to assess the distribution of individual zones of influence in a crowd and identify areas of increased density. Although this approach is widely used to analyze the structure of a crowd and identify areas of increased density of the crowd, it has limitations. Under actual conditions, a person, moving in a flow, perceives the entire open space in front of him/her to a physical obstacle as the zone of his/her movement. S/he is not guided by the virtual division of space into artificial cells.

For a more accurate reflection of actual conditions, especially at extreme events, it is proposed to determine personal space through an enlarged profile of a person until the moment of contact with the nearest person or obstacle. In this case, the smallest distance from the projection of a person to other objects is taken as the basis to determine the boundaries of the available space. This approach better describes local restriction of movement because it makes it possible to recreate the mechanism of real behavior when a person is oriented to the actual physical boundaries around him.

As shown by the review of existing models used to simulate human flows [4, 5], in most cases, a horizontal projection profile in the form of a circle is used to describe an individual person. For this case, the local crowd density is defined as:

$$D = \left(\frac{R}{R+L}\right)^2, \tag{5}$$

where R is the radius of the horizontal projection of the person for whom the local crowd density is calculated, and L is the distance to the nearest person or obstacle.

If a horizontal projection profile in the form of an ellipse is used when modeling the human flow, then the area of personal space F is determined by solving the following system of equations:

$$\begin{cases} \dfrac{(x-x_0)^2}{a^2} + \dfrac{(y-y_0)^2}{b^2} = 1, \\ \dfrac{(x-x_1)^2}{c^2} + \dfrac{(y-y_1)^2}{d^2} = 1, \\ \dfrac{x-x_0}{x_1-x_0} = \dfrac{y-y_0}{y_1-y_0}, \\ \dfrac{a}{b} = \dfrac{c}{d}, \end{cases} \tag{6}$$

where x_0, y_0 are the coordinates of the center of the ellipse describing the enlarged projection of the person for which the local crowd density is determined; a, b are the semi-axes of the enlarged ellipse; x_1, y_1 are the coordinates of the center of the ellipse describing the projection of the nearest neighbor; c, d are the semi-axes of the ellipse of the nearest neighbor.

The first two equations in system (6) describe the enlarged horizontal profiles of the projections of the person and his/her nearest neighbor, the third equation defines the straight line passing through the centers of these projections, and the fourth equation establishes the similarity between them.

The geometric representation of the problem to be solved is shown in Fig. 4.

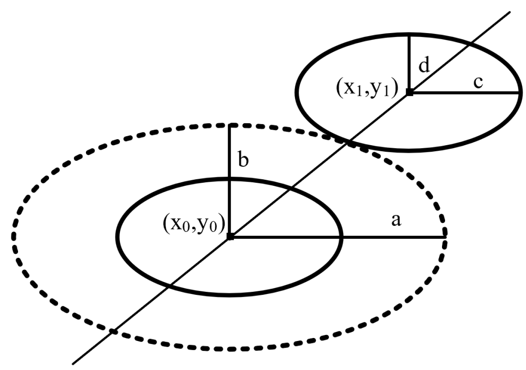


Fig. 4. Geometric representation of the interaction of two people

Having solved this system of equations, the following expressions for the semi-axes a and b are derived:

$$a = k / d, \tag{7}$$

$$b = k / c, \tag{8}$$

where $k = c \cdot d - \sqrt{c^2 (y_0 - y_1)^2 + d^2 (x_0 - x_1)^2}$.

Accordingly, the projection area of the larger ellipse is defined as:

$$S = \pi \cdot a \cdot b = \pi \cdot \frac{k}{d} \cdot \frac{k}{c} = \frac{\pi \cdot k^2}{c \cdot d}. \tag{9}$$

The local density of the crowd in the case when the projection of a person is in contact with the projection of a neighboring person is calculated using the formula:

$$D = \frac{\pi \cdot a \cdot b}{S} = \frac{c \cdot d \cdot a \cdot b}{k^2}. \tag{10}$$

For the case where the nearest obstacle is a wall, the local crowd density is determined by solving the following system of equations:

$$\begin{cases} \dfrac{(t_x - x_0)^2}{a^2} + \dfrac{(t_y - y_0)^2}{b^2} = 1, \\ \dfrac{a}{b} = \dfrac{m}{n}, \end{cases} \quad (11)$$

where x_0, y_0 are the coordinates of the center of the ellipse describing the profile of the human projection; a, b are the semi-axes of the ellipse of the human projection; m, n are the semi-axes of the enlarged ellipse describing the personal space (Fig. 5); t_x, t_y are the coordinates of the point of contact of the enlarged ellipse with the line.

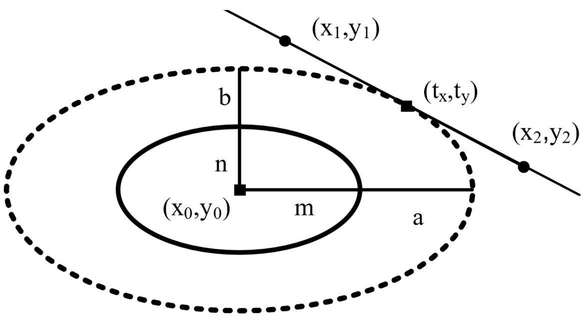


Fig. 5. Geometric representation of human interaction with an obstacle

Having solved system (11), the following expressions for the semi-axes are derived:

$$a = p / n, \quad (12)$$

$$b = p / m, \quad (13)$$

where $p = \sqrt{m^2 (t_y - y_0)^2 + n^2 (t_x - x_0)^2}$.

The projection area of an enlarged ellipse is calculated similarly (9) and is defined as:

$$S^* = \frac{\pi \cdot p^2}{n \cdot m}. \quad (14)$$

By elementary transformations, the local density of the crowd in the case when a projection of a person in the form of an ellipse is in contact with an obstacle (wall) is determined from the formula:

$$D = \frac{m^2 \cdot n^2}{p^2}. \quad (15)$$

Therefore, the established dependences (5), (10), (15) make it possible to quantitatively estimate the local crowd density taking into account the geometric parameters of the person's projection and the spatial arrangement of obstacles. The results form the basis for further adaptive determination of the desired speed of movement of a person depending on specific environmental conditions at extreme events.

5. 3. Dependence of human speed on crowd density

Paper [3] reports generalized experimental data obtained from large-scale studies. They demonstrate the dependence between crowd density and average speed of its movement at extreme events. The presented tabular experimental data cover the range of crowd density from 0.01 to 0.92 m^2/m^2.

Within the framework of this study, I have approximated the tabular experimental data by using polynomial functions relative to crowd density. For each type of movement, a separate approximation model was constructed, which makes it possible to take into account the features of different evacuation scenarios. The resulting dependences take the following form.

For movement along horizontal routes (average relative error – 0.135 %):

$$v(D) = 3.47377578 \cdot D^4 - 10.68922476 \cdot D^3 + \\ + 11.58135351 \cdot D^2 - 5.65604649 \cdot D + 1.41213058. \quad (16)$$

To move through the hole (average relative error is 0.208 %):

$$v(D) = 2.75454247 \cdot D^4 - 8.61922134 \cdot D^3 + \\ + 9.95968351 \cdot D^2 - 5.58364274 \cdot D + 1.63698151. \quad (17)$$

To move down the stairs (average relative error – 0.693 %):

$$v(D) = 4.43224673 \cdot D^5 - 11.72333803 \cdot D^4 + \\ + 11.14647521 \cdot D^3 - 3.29207523 \cdot D^2 - \\ - 1.44044860 \cdot D + 1.01350867. \quad (18)$$

To move up the stairs (average relative error – 0.627 %):

$$v(D) = -43.62194006 \cdot D^6 + 132.79782545 \cdot D^5 - \\ - 151.63959640 \cdot D^4 + 76.86192201 \cdot D^3 - \\ - 13.62044996 \cdot D^2 - 1.70825298 \cdot D + 0.94108901, \quad (19)$$

where $v(D)$ – crowd speed (m/s); D – crowd density (m^2/m^2).

The coefficients of the polynomials were determined by the least squares method based on the tabular values given in [3]. The use of polynomial approximation ensured high accuracy of the reproduction of empirical data (the average relative error does not exceed 0.7 %). This level of accuracy is sufficient for the practical use of the established dependences (16) to (19) in the problems of numerical modeling and verification of mass evacuation scenarios.

5. 4. Sequence of steps for implementing the method of adaptive determination of human movement speed at extreme events

In the absence of the need for detailed modeling of interaction between people, as well as in the cases where simulation modeling does not require strict limits on the speed of calculations, it is advisable to use an approach based on the equations of psychophysiological interaction [4, 6].

Within the framework of this approach, the basic equation of the force that initiates the movement of a person is defined as:

$$\vec{F}_i^{\,t} = m_i \frac{\vec{V}_i^{want} - \vec{V}_i}{\tau}, \quad (20)$$

where m_i is the mass of the i-th person, kg; $\vec{V}_i^{want}$ is the speed at which the person would like to move, m/s; $\vec{V}_i$ is the current speed of movement, m/s; τ is the parameter characterizing the time of involvement of the person in the panicking crowd, s.

This force is arranged in such a way that if the desired speed exceeds the actual speed, the person accelerates. If the person does not want to move anywhere, then his/her movement fades away over time.

In addition to force (20), other forces act on the person, associated with the interaction of the person with other people and obstacles [1], the consideration of which is beyond the scope of this work.

To model the behavior of the crowd under extreme conditions, a method of adaptive determination of the speed of movement of the person is proposed, which takes into account local spatial constraints when calculating the desired speed of each person.

Let $P=\{p_1,p_2,...p_N\}$ be the set of people in the crowd, and $W=\{w_1,w_2,...w_K\}$ – the set of all walls or other fixed objects that can act as obstacles.

Then, the prerequisite for using the proposed method is to assign each person $p_i \in P$ in the flow a vector of the desired direction of movement $\vec{h}_i$ and an individual effective viewing sector S_i. This sector is mathematically described as a symmetric angular sector with a vertex at the person's location, a central axis coinciding with $\vec{h}_i$, and a limiting angular half-width $\varphi_i \in [0.5°, 30°]$.

The sequence of steps for implementing the method, which are performed for each person in the crowd, is as follows:

Step 1. Determine the set of obstacles $M_i=\{x \in (P \cup W) \mid x \notin p_i, x \in S_i\}$ for the i-th person (other people or walls) that are located in the direction of movement of the person p_i and in the middle of sector S_i.

Step 2. If $M_i=\varnothing$, that is, within the viewing sector S_i there is no object that can limit the movement of the person p_i, then the local crowd density for this person is given as D_i=0.01 m^2/m^2, which corresponds to the conditions of free movement. After that, proceed to Step 5. Otherwise, at $M_i \neq \varnothing$, proceed to Step 3.

Step 3. Determine the obstacle $x_k \in M_i$ to which the distance from person p_i is minimal:

$$x_k = \arg\min_{x \in M_i} d(p_i, x), \tag{21}$$

where $d(p_i, x)$ is a function of the distance between person p_i and obstacle $x \in M_i$.

Step 4. Determine the local density D_i using equations (5), (10), or (15). The choice of a specific equation depends on the type of obstacle x_k (person or wall) and on the geometric shape of the horizontal projection of person p_i used in the model.

Step 5. Determine the desired speed of movement of person p_i:

$$\vec{V}_i^{want} = v(D_i) \cdot \vec{h}_i, \tag{22}$$

where $v(D_i)$ is determined from formulas (16) to (19) relative to the type of movement.

Reducing the desired speed during movement creates the effect of dynamic adaptation of the flow, which leads to its reformatting. As a result, a pronounced differentiation of the flow into the main, basic, and closing parts is formed, which, in turn, directly affects the time people stay in a particular area of space. This approach makes it possible to more accurately reproduce the mechanisms of crowd movement under extreme conditions.

5. 5. Testing the proposed method

To assess the effectiveness of the proposed method, it was tested by simulating crowd movement under extreme conditions similar to the scenario described in [3]. According to the case under consideration, the human flow moved along a path formed by two corridors, each 2 m wide and 20 m long. The corridors were separated in the middle by a 1 m wide opening. The initial crowd density was 0.5 m^2/m^2, with the flow occupying the first 12.5 m of the first corridor.

According to the results of calculations in [3], which are close to the data of the full-scale experiment, it takes 85.2 s (1.42 min) for the crowd to pass from one corridor to another. The approach time of the main part of the crowd (crowd density 0.05 m^2/m^2) was 6.6 s (0.11 min), while the rest reached the opening after 27.6 s (0.46 min).

During the testing, the psychophysiological approach to interaction between people in a crowd was used, which is described in [4]. For modeling, two variants of the geometric projection of a person were considered: a circular profile, which assumes a uniform distribution of personal space around the center of mass, and an elliptical profile, which is described by a three-component model that takes into account the location of the hands and torso [1].

Also, for each person in the crowd, before the start of the modeling, the limiting angle of the effective field of view was set in the range from 0.5° to 30° according to the normal distribution.

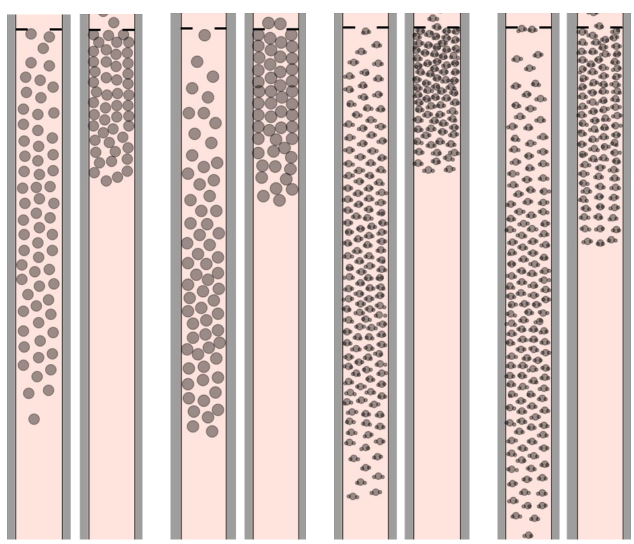
Specialized software was developed to conduct simulation modeling, which makes it possible to analyze the dynamics of crowd movement under extreme conditions. The results are shown in Table 1.

Table 1

Modeling results

Projection profile	Circle	Circle	Ellipse	Ellipse
Number of people in the crowd (density 0.5 m^2/m^2)	64	64	137	137
Application of the method of adaptive determination of human movement speed	No	Yes	No	Yes
Approach time to the opening of the main part, s	6.62	7.25	5.12	5.62
Approach time to the opening of the main part, s	13.88	23.38	17.25	28.00
Crowd leaves the corridor, s	56.12	94.62	55.75	86.88
Average modeling error, %	28.05	12.06	31.5	6.09

Fig. 6 shows the results of simulation modeling without using the devised method of adaptive determination of human movement speed under extreme conditions (Fig. 6, *a*, *c*) and when using it (Fig. 6, *b*, *d*).



a *b* *c* *d*

Fig. 6. Modeling the approach of the main and basic part of the human flow to the opening: *a*, *b* – circular projection profile; *c*, *d* – elliptical profile

As you can see in Fig. 6, depending on the use of the proposed method, there is a noticeable difference in the area occupied by the flow, as well as in the nature of its spatial organization.

6. Discussion of results based on the simulation modeling of crowd dynamics at extreme events

The results reported here indicate that the proposed method of adaptive determination of human movement speed at extreme events eliminates the key limitations of conventional approaches. In contrast to [5, 6], in which the desired movement speed is set as a fixed or discretely defined value, the devised solution provides for an adaptive change in the desired human speed in accordance with the calculated local crowd density (5), (10), (15). Such an adjustment turned out to be especially important when modeling real scenarios, when due to an increase in crowd density or sudden panic, the movement occurs unevenly and is accompanied by crowd reformatting.

Unlike approaches based on empirical data and deep learning methods [7–9], the devised method relies on universal psychophysiological and geometric factors – local crowd density and narrowing of the field of view. It does not require prior training or collection of large training data sets. In addition, in contrast to the approach in [7, 8] based on deep learning, the proposed method provides transparency and physical interpretability. At each stage of modeling, it is clearly understood which factors – crowd density, viewing angle, or spatial arrangement of obstacles – determine the desired speed and trajectory of human movement. This makes it possible to clearly explain the modeling results, compare them with real observations, and promptly determine the reasons for any discrepancies between theoretical and experimental results.

It should be especially noted that the limits of narrowing of the effective field of view of a person at extreme events determined in this work make it possible to solve the problem of comprehensive consideration of obstacles, which is characteristic of the approach reported in [10]. In addition, they reasonably adjust the limits proposed in [11], taking into account the significant narrowing of the human field of view under conditions of high stress.

The practical results of simulation modeling (Table 1, Fig. 6) simultaneously confirm the theoretical advantages of the devised method and demonstrate the shortcomings of conventional approaches. If the desired speed is constantly maximum, the crowd is reformatted too quickly and over a much smaller area (Fig. 6, *a*, *c*), which significantly overestimates the movement rate compared to actual conditions. Instead, this paper's solution takes into account tunnel vision and adaptive speed reduction, due to which the average error in movement prediction is reduced from 28.05 % to 12.06 % for the circular profile of the human projection and from 31.5 % to 6.09 % for the three-component elliptical profile. Under these conditions, the crowd deploys over a larger area (Fig. 6, *b*, *d*), and the time and nature of its movement approach the actual observation data, which confirms the high reliability of the described approach.

It is also worth noting that the study was limited to considering only two typical shapes of a person's horizontal projection (circle and ellipse). However, when considering crowds in public places such as train stations and airports, the geometric profiles of people in the crowd can differ significantly from typical ones due to the presence of baggage (suitcases, bags, backpacks) that they carry with them.

The disadvantages of the study include the fact that the devised method is focused only on a two-dimensional crowd model. In the case of its application for three-dimensional modeling, difficulties arise in taking into account the vertical limitation of the field of view. In turn, this may lead to distortion of the modeling results in situations where the height of objects significantly affects the trajectory of movement or the visibility of the space in front of a person.

Further development of the study should aim to derive analytical expressions for determining the local density of the crowd, taking into account more complex geometric profiles of a person. The results would contribute to expanding the scope of application of the devised method and increasing its versatility in modeling the dynamics of human flow at extreme events.

7. Conclusions

1. It has been established that under the influence of stressful situations, the angle limiting the effective field of view of a person can significantly narrow – up to 30° under moderate stress and up to 0.5° under conditions of extreme psycho-emotional stress. Taking this limitation into account when determining the zone of spatial analysis of obstacles makes it possible to optimize the modeling process and improve its accuracy.

2. It is proposed to determine the local density of the crowd for each person in the crowd as the ratio of the area of its horizontal projection to the area of personal space limited by the minimum distance to the nearest person or obstacle. The peculiarity of the proposed approach is that personal space is not defined by artificial cells, as is customary in Voronoi models, but by the real physical boundaries of the space around the person. Analytical expressions for calculating the local density of the crowd depending on the geometric shapes of the horizontal projection of a person (circle and ellipse) have been derived. This approach provides an individualized assessment of local crowd density, which more adequately describes the actual conditions of human movement, as confirmed by the results of simulation modeling.

3. Polynomial dependences between the density of the crowd in the range of 0.01–0.92 m^2/m^2 and the speed of its movement for different types of movement have been established. The average relative error of speed determination does not exceed 0.7 %.

4. The sequence of steps for implementing the method of adaptive determination of human movement speed at extreme events has been defined. Unlike existing approaches, the proposed method is based on calculating the desired speed of movement taking into account local spatial limitations and narrowing of the human field of view under the influence of stress. Due to this, adaptive adjustment of the desired speed of each person is performed throughout the entire modeling process, in accordance with changes in spatial conditions. In addition, the method does not require prior training or the involvement of large volumes of empirical data.

5. The proposed method for adaptive determination of human movement speed under extreme conditions was implemented in software; simulation modeling was conducted for its testing. The results indicate that the application of the proposed method leads to a more realistic and accurate reproduction of the dynamics of adaptive flow reformatting

than the conventional approach. The average modeling error decreased from 28.05 % to 12.06 % for the circular profile of the human projection and from 31.5 % to 6.09 % for the three-component elliptical profile. Taking into account psychophysiological and spatial factors made it possible to more accurately model the spatiotemporal structure of the human flow. The application of the proposed method is especially promising for predicting crowd behavior under conditions of mass panic, evacuation, or terrorist threats. The results indicate the feasibility of implementing the proposed method in automated crowd management systems, as well as in software packages developed to assess the safety of mass events and design evacuation routes.

Conflicts of interest

The author declares that he has no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The author confirms that he did not use artificial intelligence technologies when creating the current work.

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