Mathematical and Computer Modeling of Active Movement of People During Evacuation from Buildings

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Abstract. One of the forms of protecting the population from emergencies is the controlled evacuation of people from buildings for the required time, calculated on the basis of their design and planning decisions. For this purpose, scientifically sound plans for evacuation of people are developed, the main component of which are the programs of modeling of human flows, which adequately reflect the real processes of movement of people. In this work, it is proposed to take into account the natural deformation of the human body by rotating parts of its body (eg, the shoulder) when modeling flow motion. For this purpose, it is proposed to present the projection of a human body of a set of three ellipses: the main with the possibility of its rotation in the framework of maneuverability with respect to the basic direction of movement, and two ellipses, given by the half-axis's, which are equal to half the length and thickness of the shoulder with the possibility of their rotation. in a given range of angles in the horizontal plane relative to the raised arm of the person. Such a problem arises with the active movement of people in the flow of high density, when the category of movement changes from free to compressed. The paper formalizes the constraints, builds a mathematical model of the active movement of people in the flow, provides examples of computer simulation of the movement of people, which represented by a three-component models.

Keywords: Emergency Situation, Mathematical Model, Flow simulation of people in the flow, Natural deformations of the human body, Computer simulation.

1 Introduction

In the last decade, there has been a tendency for an increase in the number and scale of the consequences of emergencies. Emergencies are accompanied not only by material but also by human losses, so in the context of emergencies it is very important to make a quick and correct decision both on the elimination of the consequences of the emergency and on saving people.

1.1 Problem setting

Possible forms of population protection include the organization of guided evacuation of people from the places of emergency development, in particular from buildings for the necessary time, calculated based on their design-planning decisions. For this purpose, scientifically sound plans for evacuation of people are developed, the main component of which are the programs of modeling of human flows, which adequately reflect the real processes of movement of people. Therefore, an urgent problem is the development of models, methods and software for modeling human flows, which simplify the decision-making process for evacuation of people from

When modeling the movement of people, the following categories of movement of people on the stream are considered: free, comfortable, active, with high activity. When the movement category becomes active with possible force actions, the flow density increases. Changes in density affect the nature of the movement of people in the stream, changing it from free, in which a person can choose the speed and direction of his movement, to compressed movement, in which he feels the growing force effect of others.

Therefore, an important and unresolved part of the problem is the development of models, methods and software of active movement of people, taking into account the natural deformation of their bodies.

1.2 Paper objective

The purpose of the article is to analyze the active movement of people with force action and develop models of the human body, taking into account its natural deformities and modeling the active movement of people taking into account their forceful contacts during movement.

To achieve this goal, you need to solve the following tasks:

- to build a model of the human body taking into account its natural deformities;
- to formalize of the constraints of the task;
- to develop a model and algorithm for modeling the active movement of people taking into account their natural deformations:
- to carry out computer simulations of the movement of the flow of people by force action.

1.3 Recent research and publications analysis

An empirical basis for full-scale observations of human flows in buildings of various purposes, which were oriented by theoretical studies [1, 2], although it was the largest in the world in the 1960s, but was only a quarter of that already accumulated by the end of the 70's of the last century. The quantitative diversity of the results of the series of field observations has raised the problem of theoretical substantiation of the observed dependencies between the parameters of human flows. A grapho-analytical method for calculating human flows has emerged [1, 2], although it is laborious for design-planning of practice and does not sufficiently fully reflect the verbal description of the process of human movement.

There was a problem of mathematical description of the dependencies between the parameters of human flows and the description of changes in the states of the flow (its displacements) in space. Difficulties in modeling human flows and ignorance of their patterns led to attempts to replace the processes of motion of real human flows by models of processes of a different physical nature. For example, they model the parameters of human flows using an stream of requests or a hydroanalogy instead [3, 4].

Other analogies and related computer programs are also possible. The western software market provides a large number of such examples [5]. Such approaches are not new to modeling methodology and have long received their appreciation in the scientific literature: “Some are interested in the structure and regularities of the phenomena that lead to the observed result, others - only the results themselves. The first, when modeling, try to reproduce the structure and regularities of the phenomenon, the second - only the results, without resorting to the real mechanisms of their appearance [6].

Currently, “Floutec” software products for simplified analytical and simulation-stochastic models and “Evatec” [7–8] for the individually-flowing model of humans flow motion are distributed. But the results of the analysis [7] show that there is no model of individually-current movement of people, adequate to the real flow, for people with limited mobile possibilities of mixed composition in a rather wide nomenclature of public buildings of different classes of functional fire danger.

In [9–10], the problem of modeling the motion of heterogeneous flows of people (people are represented by ellipses) is posed and solved, which boils down to the problem of dense accommodation (displacement) of people with different densities, that is, of their location at each moment of time, taking into account different minimum allowable distances between them according to a number of additional technological restrictions, among which it is possible to distinguish the movement at different speeds, taking into account their maneuverability, comfort of movement, etc.

According to [11] the following categories of motion are observed in the movement of people in the stream: comfortable, calm, active, with high activity. Model [9] can be used for comfortable and free movement of people.

When the traffic category changes and becomes active traffic category with possible force actions, the flow density increases [11]. Density changes have a strong influence on the character of the movement of people in the stream, changing it from free, at which a person can choose the speed and direction of his movement, to compressed movement as a result of a further increase in the density of the flow, in which he feels the increasing force of the surrounding people.

2 Presentation of the main research material

A plurality of people simultaneously walking the common section (area) in one direction forms a human stream [11]. The parameters of the human flow are: the number of people in the stream *N*, the density *D*, the velocity $\vec{v}$, the magnitude of the flow *P*, that is, the number of people passing through the cross-section of the section occupied by set of humans in the unit time. It should be noted that the free space in the flow depends not only on the number of persons, but also on the area occupied by each of them, so the size of people play a role. To account for this factor, it was proposed to enter into the calculation of the density of the flow the area occupied by the person (area of horizontal projection f_i, m^2) [8, 11]:

$$D_i = \frac{N_i f_i}{b_i l_i}, m^2 / m^2$$

In [9–11], the horizontal projection of a person is taken as an ellipse whose diameters (a_i, c_i) correspond to the width and thickness of the human body. Comfort, which takes into account the natural movements of man, is given by the minimum permissible distances Δδ between people, which takes into account the equidistant lines at a distance Δδ from ellipses, which describe the projection of human bodies on a plane xOy [9].

2.1 Building a model of the human body taking into account its natural deformities

In this work it is proposed to take into account the natural deformation of a human body by rotating parts of his body (eg, the shoulder) when modeling movement. For this purpose it is proposed to represent a human projection by a set of three ellipses: by the main with the possibility of its rotation in the limits of the maneuverability relative to the main direction of movement, and by two auxiliary ellipses according to semi-axes equal to half the length and width of the shoulder with the possibility of their rotation in the range of angles (-α2; + α1) in the horizontal plane relative to the raised arm of the person. Thus, to construct a model of the human body, it is proposed to represent its projection in the form of a non-rigid connection of three ellipses: E_c with the dimensions of the half-axes *A* and *B*, and E_l and $E_r$with the sizes *a* and *b* (see Fig. 1). Each object *E* is associated with placement parameters $u = (v, \theta)$, where $v = (x, y)$ is the object's *E* translation vector relative to the fixed coordinate system, and θ is the angle of its rotation. In this case, an arbitrary point $p = p(0)$ of the object is mapped to the point $p(u) = v + M(\theta) p^T(0)$, where $M(\theta)$ is the matrix of the operator of rotation of space by an angle $\theta = \phi$ (see Fig. 2).

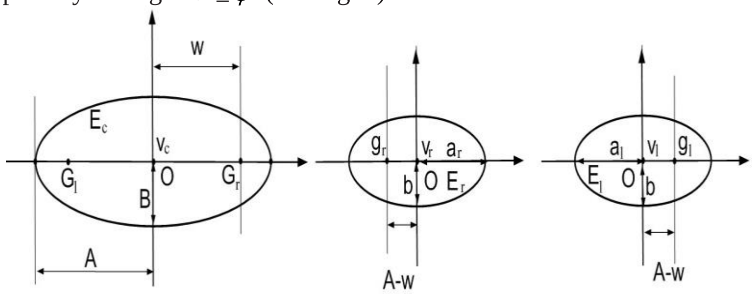


Fig. 1. Three components of the human body model: trunk, right shoulder, left shoulde.

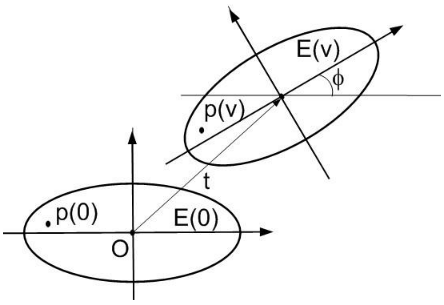
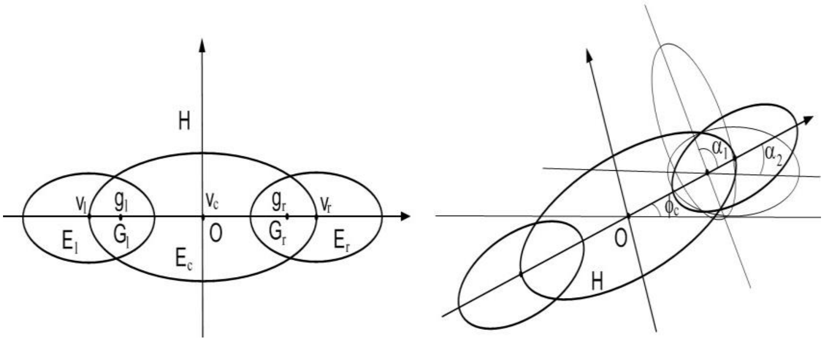


Fig. 2. Illustration to the parametric description of the position of the ellipse on the plane

Let $E(u)$ denote the object $E = E(0)$ rotated by the angle $\theta = \phi$ and translated onto the vector v. The pairs of points G_l, g_l and G_r, g_r, marked in the first figure (Figure 3 a) are used to "glue" the components of the model into a single object H (see Fig. 3 a).

In addition to gluing conditions, a restriction on the ratio of rotation angles is imposed on the relative position of the objects, which follows from physical restrictions on the relative position of parts of the human body (see Fig. 3). Thus, the rotation angle θ_r of an ellipse E_r cannot be greater than the angle $\theta_c + \alpha_1$ and less than $\theta_c - \alpha_2$, where θ_c is the angle of rotation of the object E_c (see Fig. 3 b). Accordingly, the rotation angle θ_l of the ellipse E_l cannot be greater than the angle $\theta_c + \alpha_2$ and less than $\theta_c - \alpha_1$.



a) b)

Fig. 3. A three-component model of the human body with the following restrictions: (a) conditions for gluing the components of the model into a single object, (b) restrictions on the mobility of the ellipse modeling the human shoulder

Thus, it is proposed to use an object $H_i(u_{ci}, u_{li}, u_{ri})$ with the following restrictions on the placement parameters as a model of the projection of the human body:

$$g_l(u_l) = G_l(u_c), \tag{1}$$

$$g_r(u_r) = G_r(u_c), \tag{2}$$

$$\theta_c - \alpha_2 \le \theta_r \le \theta_c + \alpha_1 , \quad (3)$$

$$\theta_c - \alpha_1 \le \theta_l \le \theta_c + \alpha_2 \quad (4)$$

It should be noted that in conditions of high density of people, the variables a_l and a_r can be included in the number of variable parameters of the model with limitations of the next form

$$\alpha_0^{'} \le \alpha_l \le \alpha_1^{'}, \alpha_0^{'} \le \alpha_r \le \alpha_1^{'}, \quad (5)$$

allowing to take into account the vertical rotation of the shoulder joint in the model. The values of variables $\alpha_0^{'}, \alpha_1^{'}$ is also determined by physical restrictions on the relative position of the parts of the human body and is selected from the anthropological data of the individual.

We will construct a mathematical model of the problem of modeling the movement of people represented by a three-component model, for which we formalize the constraints and the goal function of the task.

2.2 Formalization of the constraints of the task

We will describe the conditions for the non-intersection of two objects $H_i(u_{ci}, u_{li}, u_{ri})$ and $H_j(u_{cj}, u_{lj}, u_{rj})$ based on the modification of the quasi-phi function [12] for the case of composite non-rigidly connected objects. It should be noted that when modeling the movement of streams of people at each discrete moment of time, there is a configuration of the placement [13] of objects that approximate the human body.

According to the definition [12], a quasi-phi-function $\Phi^{'E_i E_j}(u_i, u_j, t_{ij})$ for objects $E_i(u_i)$ and $E_j(u_j)$ is defined as a everywhere defined continuous function in all variables, for which the function $\max_{t_{ij} \in U \subset R^m} \Phi^{'E_i E_j}(u_i, u_j, t_{ij})$ is the phi-function of $E_i(u_i)$ and $E_j(u_j)$. Here t_{ij} is the vector of auxiliary variables that belong to a certain subset U of the space R^m (as shown in [12], $m=1$ and U coincides with R^1).

Further, we use the following important characteristic of a quasi-phi function: if for some t_{ij} it holds $\Phi^{'E_i E_j}(u_i, u_j, t_{ij}) \ge 0$, then $\text{int}\, E(u_i) \bigcap \text{int}\, E(u_j) = \varnothing$ [12].

As is known [14], for two composite objects $T_i(u_i) = \bigcup_{k=1}^{n_i} T_{ik}(u_i)$ and $T_j(u_j) = \bigcup_{k=1}^{n_j} T_{jm}(u_j)$ a quasi-phi-function can be written as

$$\Phi^{'T_i T_j}(u_i, u_j, t_{ij}) = \min\{\Phi^{'T_{ik} T_{jm}}(u_i, u_j, t_{ij}), k = 1,..., n_i, m = 1,..., n_j\}, \quad (6)$$

where t_{ij} is the vector of auxiliary variables $t_{ijkm}, k=1,...,n_i, m=1,...,n_j$.

We write the condition of non-intersection of two objects $H_i(u_{ci},u_{li},u_{ri}) = E_{ci}(u_{ci}) \bigcup E_{li}(u_{li}) \bigcup E_{ri}(u_{ri})$ and $H_j(u_{cj},u_{lj},u_{rj}) = = E_{cj}(u_{cj}) \bigcup E_{lj}(u_{lj}) \bigcup E_{rj}(u_{rj})$ in the form of a function $\Phi'^{H_iH_j}(u_{ci},u_{ri},u_{li},u_{cj},u_{rj},u_{lj},t_{ij}) \ge 0$. Based on (6), a function $\Phi'^{H_iH_j}(u_{ci},u_{ri},u_{li},u_{cj},u_{rj},u_{lj},t_{ij})$ can be represented as:

$$\begin{aligned}
&\Phi'^{H_iH_j}(u_{ci},u_{ri},u_{li},u_{cj},u_{rj},u_{lj},t_{ij}) = \min\{\Phi'^{E_{ci}E_{cj}}(u_{ci},u_{cj},t_{ij1}),\\
&\Phi'^{E_{ci}E_{lj}}(u_{ci},u_{lj},t_{ij2}), \Phi'^{E_{ci}E_{rj}}(u_{ci}u_{rj},t_{ij3}), \Phi'^{E_{li}E_{cj}}(u_{li},u_{cj},t_{ij4}),\\
&\Phi'^{E_{li}E_{lj}}(u_{li},u_{lj},t_{ij5}), \Phi'^{E_{li}E_{rj}}(u_{li},u_{rj},t_{ij6}), \Phi'^{E_{ri}E_{cj}}(u_{ri},u_{cj},t_{ij7}),\\
&\Phi'^{E_{ri}E_{lj}}(u_{ri},u_{lj},t_{ij8}), \Phi'^{E_{ri}E_{rj}}(u_{ri},u_{rj},t_{ij9}).
\end{aligned} \tag{7}$$

As can be seen from (7), the conditions for describing the non-intersection of constructed objects are based on the description of the conditions for non-intersection of ellipses.

As follows from [9, 15], the conditions for the mutual non-intersection of ellipses are described by the inequality $\Phi'^{E_iE_j}(u_i,u_j,t_{ij}) \ge 0$, where the quasi-phi-function $\Phi'^{E_iE_j}(u_i,u_j,t_{ij})$ can be written as:

$$\begin{aligned}
&\Phi'^{E_iE_j}(u_i,u_j,t_{ij}) = (x_i - x_j)\cos t_{ij} + (y_j - y_i)\sin t_{ij} - R_i -\\
&\sqrt{b_i^2 + (a_i^2 - b_i^2)\cos^2(\theta_i - t_{ij})} - \sqrt{b_j^2 + (a_j^2 - b_j^2)\cos^2(\theta_j - t_{ij})}.
\end{aligned} \tag{8}$$

It should also be noted that the quasi-phi function (6) is normalized, i.e. $\max_{t_{ij} \in U \subset R^m} \Phi'^{E_iE_j}(u_i,u_j,t_{ij})$ there is a normalized phi-function of objects $E_i(u_i)$ and $E_j(u_j)$, and in value coincides with the distance between objects $E_i(u_i)$ and $E_j(u_j)$.

To formalize the conditions of belonging an object $H_i(u_{ci},u_{li},u_{ri}) = E_{ci}(u_{ci}) \bigcup E_{li}(u_{li}) \bigcup E_{ri}(u_{ri})$ of area Ω (Ω is a rectangular region with vertices $v_1 = (0,0)$, $v_2 = (L,0)$, $v_3 = (L,W)$, $v_4 = (0,W)$, respectively), we use a normalized phi-function that is built on the basis of an analytical description of the conditions of belonging Ω projections of ellipses $E_{ci}(u_{ci}), E_{li}(u_{li}), E_{ri}(u_{ri})$ on the axis of the global coordinate system in which the domain Ω is defined.

So, an object $H_i(u_{ci}, u_{li}, u_{ri}) = E_{ci}(u_{ci}) \bigcup E_{li}(u_{li}) \bigcup E_{ri}(u_{ri})$ belongs to a rectangular region Ω if the negative phi-function is:

$$\Phi^{H_i\Omega^*}(u_i) = \min_{k=1,...,4}(\min(f_{ik_c}(u_{ci}), f_{ik_l}(u_{li}), f_{ik_r}(u_{ri}))) \quad (9)$$

where $\Omega^* = R^2 \setminus \Omega \ \forall i \in \{ci, li, ri\}$ and are performed:

$$f_{i1}(u_i) = x_i - a_i^*, \ f_{i2}(u_i) = y_i - b_i^*, \ f_{i3}(u_i) = L - x_i - a_i^*, \ f_{i4}(u_i) = W - y_i - b_i^*,$$

$$a_i^* = \sqrt{a_i^2 \cos^2\theta_i + b_i^2 \sin^2\theta_i} = \sqrt{b_i^2 + (a_i^2 - b_i^2)\cos^2\theta_i}$$

$$b_i^* = \sqrt{a_i^2 \sin^2\theta_i + b_i^2 \cos^2\theta_i} = \sqrt{b_i^2 + (a_i^2 - b_i^2)\sin^2\theta_i} \ .$$

Conditions (7), (9) are supplemented by the following restrictions:

$$g_{li}(u_{li}) = G_{li}(u_{ci}), \ g_{ri}(u_{ri}) = G_{ri}(u_{ci}), \ \theta_{ci} - \alpha_2 \le \theta_{ri} \le \theta_{ci} + \alpha_1,$$

$$g_{lj}(u_{lj}) = G_{lj}(u_{cj}), \ g_{rj}(u_{rj}) = G_{rj}(u_{cj}) \ \theta_{cj} - \alpha_2 \le \theta_{rj} \le \theta_{cj} + \alpha_1, \quad (10)$$

$$\theta_{cj} - \alpha_1 \le \theta_{lj} \le \theta_{cj} + \alpha_2, \ \theta_{ci} - \alpha_2 \le \theta_{ri} \le \theta_{ci} + \alpha_1$$

Thus, work formalized the limitations of the problem of modeling the active movement of people taking into account their natural deformations (functions (7)-(10)).

2.3 Development a model and algorithm for modeling the active movement of people taking into account their natural deformations

Let the initial data on the paths of movement of individuals be given in the form shown in Fig. 4

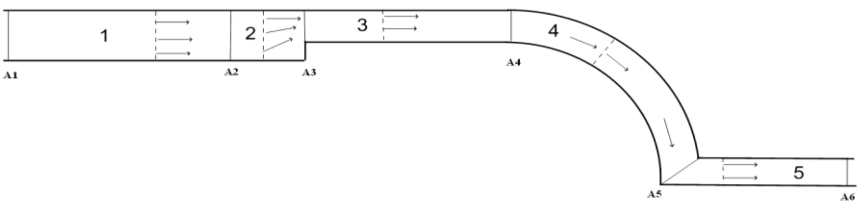


Fig. 4. Presentation of the path of movement

Each area is characterized by the same law of formation of the basic direction of movement. The main direction of movement from a point for a zone with rectilinear movement is specified by a vector connecting points of separators A_m and A_{m+1} (taking into account the homothetic coefficient). The definition of the main direction of movement for this case is clearly illustrated in the figure for the second zone.

Suppose that at the *k*-th iteration (with a given time interval Δt , for example, 1 s) in the evacuation area Ω_m there are N_k people with placement parameters $u_{ci} = (x_{ci}, y_{ci}, \theta_{ci})$, $i = 1,2, ..., N_k$, where (x_{ci}, y_{ci}) are the coordinates of the location of the beginning of the local system of coordinates (current point), and θ_{ci} - the angle of rotation of the *i*-th ellipse $E_{ci} \subset H_i$ with the size of the half-axes (A_{ci}, B_{ci}) .

Since the model of the *i*-th person is a three-component model $H_i(u_{ci}, u_{li}, u_{ri}) = E_{ci}(u_{ci}) \bigcup E_{li}(u_{li}) \bigcup E_{ri}(u_{ri})$, the values (x_{li}, y_{li}) and (x_{ri}, y_{ri}) are chosen from the anthropological data of the person, and the angles θ_{li} and θ_{ri} determine the spatial shape of the three-component model, so the variable parameters of the model are the parameters $x_{ci}, y_{ci}, \theta_{ci}, \theta_{li}, \theta_{ri}$, that is $H_i(x_{ci}, y_{ci}, \theta_{ci}, \theta_{li}, \theta_{ri})$. Note that the large half-axis of the ellipse E_{ci} is perpendicular to the direction of motion, and the angle of rotation θ_{ci} of the ellipse E_{ci} is determined between the perpendicular to the major half-axis and the vector of the main direction of motion and is determined within the maneuverability m_{ci} , m_{ci} <1 (in meters). The object E_{ci} is also assigned speed characteristics $\vec{v}_{ci}$ (in meters per second).

The mathematical model of the subtask for the *k*-th iteration in the form of finding the maximum of the total displacement of people N_k in the area of evacuation behind time Δt , i.e.

$$F(u^*) = \max_{u \in W_k \subset R^n} F(u), \; F(u) = \Delta t \sum_{i=1}^{N_k} \Delta t_i \left| \vec{v}_{ci}(x_{ci}, y_{ci}, \theta_{ci}, \theta_{li}, \theta_{ri}) \right|, \tag{11}$$

$$u = (t_1, z_{c1}, x_{c1}, y_{c1}, \theta_{c1}, \theta_{l1}, \theta_{r1}, t_2, z_{c2}, x_{c2}, y_{c2}, \theta_{c2}, \theta_{l2}, \theta_{r2} ...,$$
$$t_{N_k}, z_{cN_k}, x_{cN_k}, y_{cN_k}, \theta_{cN_k}, \theta_{lN_k}, \theta_{rN_k}).$$

The domain of permissible solutions w_k is defined by the constraints on the conditions of non-intersection and the conditions of placement of objects $H_i(x_{ci}, y_{ci}, \theta_{ci}, \theta_{li}, \theta_{ri})$, $i \in I_{N_k}$ (7), (9), restrictions (10) on the boundary of natural deformations of human body, technological limitations on the relative motion time Δt_i of the *i*-th person and on the angles of their rotation, which are determined within the maneuverability of movement:

$$T_i \geq 0 : \begin{cases} 0 \leq \Delta t_i \leq 1, \\ -m_{ci} \leq z_{ci} \leq m_{ci}, i \in I_{N_k} \end{cases},$$

$$n = 7N_k + \frac{N_k(N_k - 1)}{2}.$$

The properties of the model are investigated and the ways of solving the problem are proposed: as non-linear programming problems and as geometric modeling of move people with optimization by a group of variables, which includes human placement parameters.

This paper proposes an algorithm for solving a problem, which is presented as a sequence of the following steps.

Algorithm.

Step 1. The evacuation area is set as a tree (graph). Rebs - segments of corridors, vertices - intersections and points of "gluing" of segments. A segment can have a variable width (which varies linearly). For each segment point, the distance to the exit and the direction of the predominant movement are calculated.

Step 2. A mesh with a small enough step to determine the flow density is superimposed on the evacuation area.

Step 3. The three-component human models are sorted by increasing distance to the exit.

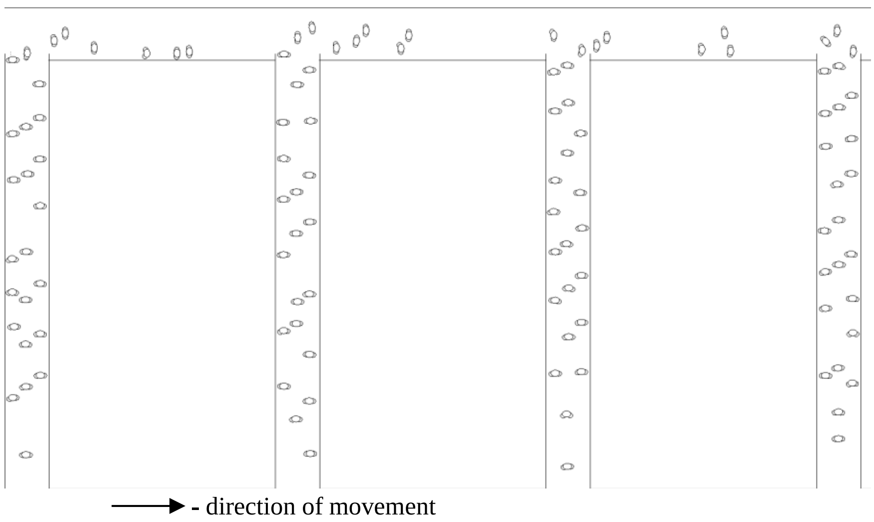
Step 4. In order of sorting, for each of the people in the coordinates of the position of the center and the angle of rotation are determined by the local flux density and the predominant direction of movement.

Step 5. For the selected preferred direction of movement within the maneuverability angle, a finite number of directions is determinedю For each of the directions within the constraints on the angles of rotation of the parts of the human body, the finite number of angles of rotation of the auxiliary ellipses of the three-component human model is analyzed.

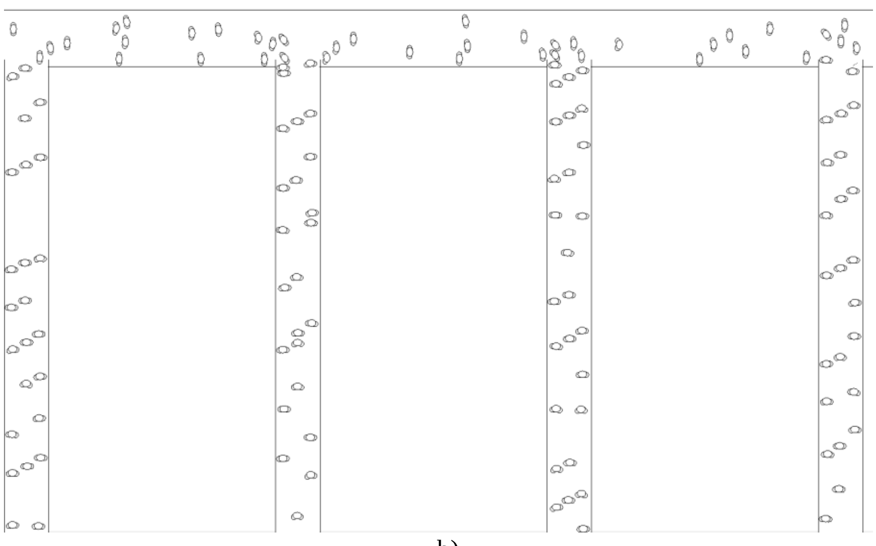
Step 6. Among the angles of maneuverability and the corresponding angles of rotation, which simulate the relative position of parts of the human body, rational parameters are found, which allow for a unit of time to make the maximum movement without violations of the boundaries of the segments and without intersection with other ellipses. (The speed of movement is adjusted by the local flux density).

2.4 Computer simulations of the movement of the flow of people by force action

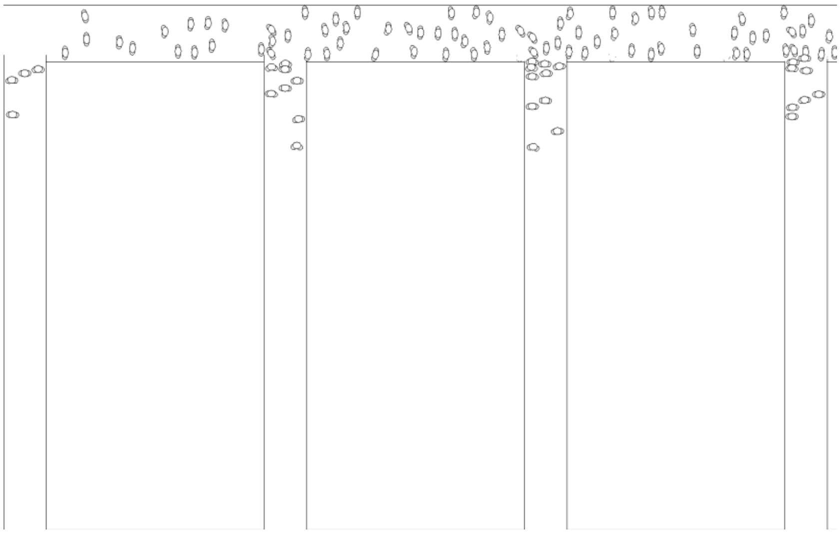
The algorithmic support for computer simulation of the optimization of objects' moving was created. The program was developed in the Microsoft Visual Studio 6.0 environment to simulate the process of evacuation of people. As an example and to compare the results, the problem is solved from the manual [11] modeling the movement of people in four corridors 18 m long and 1.65 m wide with a merger into one stream, which moves to the exit on the main corridor. Main corridor has 1.6 m wide and 70 m long and which consists of three sections of 10 m and a section of 40 m to the exit. At the initial time, 28 people are accommodated in each of the four corridors; the initial flow density is set at 1.47 people / m2. In modeling, people are represented by a three-component model. The velocity is adjusted depending on the local flow density, which is obtained in [11] experimentally. The maneuverability of people is selected from the range [-0.5; +0.5] m. The evacuation process is presented in four fragments in Fig. 5.



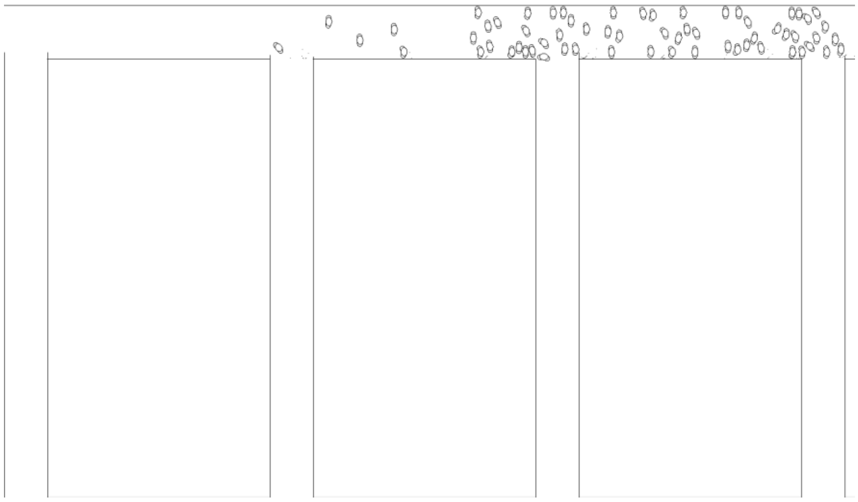
a)



b)



c)



d)

Fig. 5. Computer modeling of active movement of people. The configuration of the placement of people, respectively: a) for 7 s, b) for 10 s, c) for 15 s, d) for 30 s of movements

Figure 6 shows a fragment of modeling the movement of people at the moment in time shown in Figure 5.c when leaving the third corridor to the main one.

The authors of the manual obtained an evacuation time of 93 s, and when using this approach - 90s, the absolute error is 3 s, and the relative - 0.03 (3%). The reduction of evacuation time is observed due to the faster "scattering" of crowds, which is observed in the simulation process.

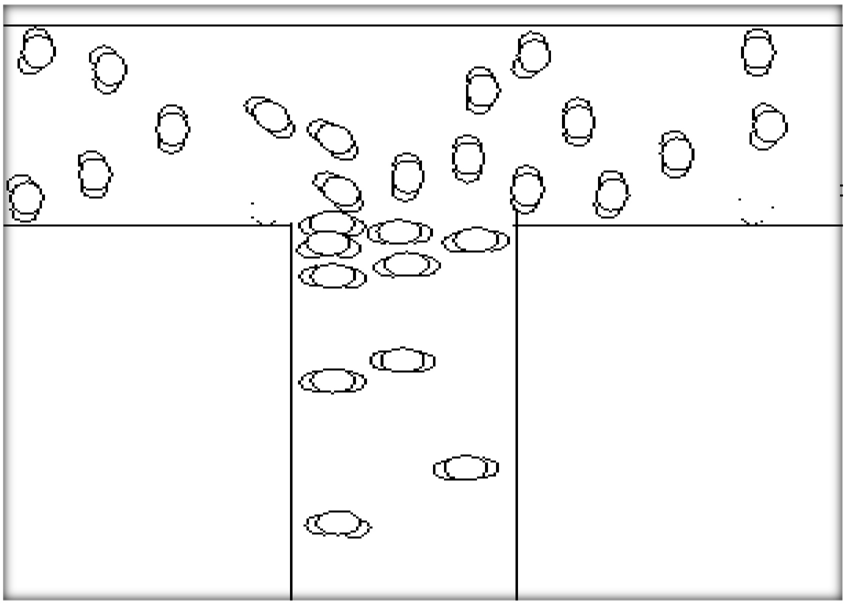


Fig. 6. The position of the people represented at moment in time, which represented by fig. 5.c

3 Conclusions

The anthropological features of a person are analyzed and a three-component model of the human body is proposed, which takes into account the conditions of bonding of the model component into a single complex object and the ratio of rotation angles of the model component arising from physical limitations to the mutual position of body parts. This human model allowed simulating the movement of people along the stream, taking into account their forceful actions that occur with their active movement. The developed mathematical model expands the class of solved tasks of modeling the movement of people. For the constructed three-component model of the human body, analytical expressions of the conditions of their non-intersection and placement in the area, which is the basis of the mathematical model of modeling the movement of people taking into account the force actions between them, were obtained.

The mathematical model is proposed and the algorithm of simulation of active movement of people taking into account natural deformations of bodies is modified. The modification is to take into account the natural deformations of the human body as a three-component's models. The properties of the model in the future will allow you to present the task as a classic task of nonlinean programming and use existing optimization packages. Computer simulation of the movement of people in the stream was carried out taking into account the natural deformations of bodies that occur in their active movement. The results can be used to quickly decide on the choice of evacuation routes in case of emergencies.

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