Usage of receptor (voxel) geometric models in the tasks of evaluating the ergonomics of engineering equipment of building structures

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Abstract. The article considers the task of automated layout of engineering equipment in construction (mechanical, electromechanical, climatic and other auxiliary equipment of civil and industrial buildings). As part of this task, the issue of ensuring the ergonomics of the layout is investigated, by which we mean the possibility of delivery of installation tools to their places of use and the availability of sufficient space for their work. A new approach is proposed, in which the tool trajectory is formed from the initial position to the point of use, as well as the space required for installation operations. The set of instantaneous positions of a movable tool is modeled as a solid object that composes in a scene. The efficiency of using receptor (voxel) geometric models for this purpose is shown. They allow not only to easily determine cases of their mutual intersection, but also to form intelligent layout algorithms. The possibilities of using 6 digit receptor models are shown, which facilitates the analysis of the layout situation, the use of receptor models to determine the shortest distances to obstacles and the output parameters of the trajectory formation program in C#. The effectiveness of the developed model for evaluating ergonomics.

1. Introduction

The quality of the design of any equipment, especially mechanical structures, is largely determined by the quality of the layout of any placed elements of this structure. And although in building structures the requirements for its maximum density and for ensuring the given alignment (as with the layout of transport objects) are not presented for the layout, the requirements for ensuring the ergonomic layout become a very important quality criterion. This difficult formalized requirement directly affects the convenience of the subsequent functioning of the designed objects (for example, engineering systems of buildings). Their maintenance is facilitated, which leads to increased safety and increased operating life of these structures [1,2].

The traditional way to ensure the ergonomic layout was physical modeling of the serviced objects (Figure 1 a) and geometric modeling of service areas by the installer (Figure 1 b) [3,4]. For greater clarity, the process of evaluating the ergonomics of the layout on the basis of ergonomic tables creates the so-called physical somatographic mannequins (both flat and spatial - Figure 2) [5]. In Figure 2 b it can be seen that for such dummies the possibility of modeling a large number of various poses is available.
The development of information technology in building design has not spared ergonomic design of structures. With the development of digital technologies (primarily geometric modeling systems), it became possible to create an electronic product model with solid-state modeling of all objects placed in it [6 - 9]. The advantage of this approach is not only the ability to visualize all structural solutions (up to the release of drawings), but also the ability to extract a large amount of additional information (for example, identifying cases of mutual intersection of all components of a simulated scene). Almost all modern systems of geometric modeling (SGM) possess such capabilities (KOMPAS, SolidWorks, AutoCAD, etc.). This gave a powerful impetus to the creation of electronic somatographic mannequins of varying complexity (Figure 3). The great advantage of using such dummies is that these dummies are perceived as solid-state models by geometric modeling systems, which, in turn, makes it possible to determine the intersection of this dummy with other objects of the virtual scene.

![Figure 1. Physical modeling of serviced objects (a) and geometric modelling of service areas (b).](image)

![Figure 2. Flat (a) and spatial (b) of physical somatographic mannequins.](image)

In the same way, the participation of mannequins in various installation operations can be modeled (Figure 4). At the same time, the virtual dummy of the installer and his working tool is inserted into the scene as a solid-state object with parameters specified by the user of the SGM. All parameters of the scene in this case will be a visualization of the design experience and spatial thinking of this CAD user, the results of which will not always be not only rational, but even acceptable. Such an approach can only be considered as an advanced means of visualization of previously adopted structural solutions.

A more complex (from the geometrical point of rhenium) case is the arrangement of objects with regard to ergonomic requirements. By them we mean the possibility of installation and maintenance of
the equipment being placed, i.e. the possibility of not only delivering it to a given installation point, but also the convenience of working with the installation tools necessary for its installation / disassembly. Such operations are encountered when installing electrical installations, elevators, air conditioners, etc. in buildings (Figure 3).

![Figure 3. Computer somographic mannequins of varying complexity.](image1)

![Figure 4. Visualization of work operations through virtual somographic 3D mannequins.](image2)

However, we will consider the possibility of an automated assessment of the ergonomics of the layout. We will be interested in the issue of ensuring the possibility of installation and maintenance of the selected layout option. Unfortunately, using the “direct” capabilities of geometric modeling systems does not solve the issue of evaluating the ergonomics of a layout. Using the electronic layout of the layout does not give us recommendations on how to deliver the installation tool to the working area, whether there is enough working space for it and whether a person is able to control the tool in that limited space. Such a statement of the problem of our study is much more complicated than solving the question of the convenience of the pose of the somographic dummy.

2. Using of geometric modeling in tasks of automated layout, taking into account the ergonomic factor

Since the task of automating the placement of equipment is a classic geometric placement problem, the most effective solutions should be sought in the library of geometric modeling methods. In our previous publications [10-12], the possibility of using receptor (voxel) methods of geometric modeling in problems of automated equipment layout was shown. Recall that, in its geometric essence, the receptor method is a method of discretization of space, in which a 3D body is approximated by individual elementary volumes (receptors). A receptor is considered excited if the boundary of an object passes through it or if it belongs to an internal region. The English language analogue of the term "receptor" used in foreign scientific literature is the word "Voxel" - "voxel" (an abbreviation for the words "VOLUMetric" and "piXEL"), i.e. three dimensional pixel (Figure 5) [13,14].
Figure 5. Receptor (voxel) model of a 3D body.

The advantages of receptor models are the ability to relatively easily determine the conditions for mutual non-intersection of composable objects. Their other advantage is the ability to describe geometric shapes of any complexity. Receptor models also have disadvantages - the need for significant computer resources for their implementation. However, at the present time, the build-up of operational computer memory does not cause either technical or economic difficulties. Although receptor models are intramachine, the task of forming receptor models of objects of any complexity has been solved [15,16].

In our approach to automated layout, ergonomics means assessing the possibility of installation and maintenance of already installed equipment. This means that it is not only the possibility of its delivery to a given installation point, but also the availability of sufficient for working with these installation tools (for example, when installing electrical equipment, elevators, air conditioners, etc. in buildings). The same problems arise when it is necessary to move oversized cargo to the installation point within the limited spaces of the construction site [17-19].

The complexity of the task from the geometric point of view is that we must form a set of instantaneous positions of the tool moved to the working area and a set of instantaneous positions of its working movements (Figure 6 a). This set of instantaneous movements will be considered by using as a composable object, which we will try to “fit” among already placed objects [20-22].

Obviously, the object formed in this way (the set of instantaneous movements of the instrument) will be extremely complex in its geometric shape. Moreover, the most important requirement for its geometric description is the possibility of its transformation in a certain direction when identifying cases of its intersection with already arranged objects. These requirements, in our opinion, exclude the use of analytical methods for describing the form. The only way to form a geometric model of an object so complex in its shape with the possibility of its unpredictable modification is seen in using only receptor (voxel) models.

But receptor models make it possible and relatively easy to identify areas of intersection of the tool path with other objects in the scene (Figure 6 b). When identifying cases of intersection of the trajectory with already placed objects, we will either have to change the trajectory of the tool, or select another tool, or recognize the investigated layout option as non-ergonomic.

3. Usage of multi-valued receptor (voxel) matrices

As already noted, receptor models are intramuscular. Three dimensional objects are described by a three dimensional matrix $A = \{a_{i,j,k}\}$ of dimension $m \times n \times p$. In this case, the fact of the excitation of the receptor is its coincidence (incidence) with the space occupied by the simulated object. The excited receptor is assigned the code "1", the non-excited receptor – "0".

An important feature of our approach, which differs from the use of receptor models in their classical form, is the use of multi-valued receptor matrices. In our case, receptor matrices will not be 2 digit, but 6 digit. An illustration of this is shown in Figure 7, in which, for clarity of perception, a receptor matrix with “large” receptors is considered.

In the initial receptor matrix, there are already placed objects (forbidden areas) with the code «1» and free space (receptors with the code "0"). Now, what is being added in our approach. There is a working tool in the initial position, which is denoted by the code "2" (for example, this is an open end wrench). It must be carried to a certain place and carried out with its help the required technological operations (for example, tightening the nut) to the point indicated in Figure 7 green. The starting and ending points of the tool position in Figure 7 do not have personal codes, since their position in space
will be set by the initial data of the program that implements the movement algorithm. The workspace required for installation operations is indicated in Figure 7 receptors with a code of "3". The tool trajectory constructed for performing this operation is shown in Figure 7 area of receptors with a code of "4". It can be seen that the formed path intersects the already arranged objects, and at the places of this intersection the receptor code changes from "1" to "5". The use of 6 digit codes in the receptor matrices, with some complication of the modeling method, allows you to obtain additional information about the problem areas in the studied layout (impossibility of carrying the instrument, impossibility of performing installation operations, etc.).

![Figure 6](image6.png)

**Figure 6.** The set of instantaneous positions of the moved tool in front view (a) and top view (b); representation of these movements by the solid-state model (c).

![Figure 7](image7.png)

**Figure 7.** Using of a multi-valued receptor matrix.

The analysis depicted in Figure 7 of the layout situation shows that using the selected working tool, it is possible to service the required object (tighten / unscrew the nut), but to bring the tool to the right place - not yet - two of the already placed objects interfere. This is bad, but not fatal - you can modify the trajectory (for example, lower it below the first obstacle and change the orientation of the tool when moving it) in order to bring the working tool to the desired point. Receptor models have the potential to form a rational tool path.

4. The formation of the trajectory of movement of the working tool to the point of using

Unfortunately, the solution to the problem of designing a path for moving a tool to a place of using is not amenable to numerous classical methods of the theory of automatic control, since in our case there are no necessary mathematical models of the control process.
Another class of solutions is associated with the search by the robot (ground or multicopter) for an algorithm to overcome obstacles [23-27]. These methods are based on learning algorithms. There are known approaches to motion control, in which artificial neural networks (ANNs) are used as a tool for evaluating, predicting parameters and directly controlling the motion of the control object.

A common disadvantage of such approaches is that the optimal robot path is developed during its training, i.e. repeated passage of the route, which is impossible in our case, a one-time selection of the trajectory. In addition, in ANN approaches, the source of training is information obtained through a vision system (for example, from a locator), which allows you to determine the coordinates of obstacles in the area of its operation.

In our case, the tool moved to the point of using, if we consider it as a control object, does not have location tools to identify nearby obstacles, and does not have “experience” that allows us to generalize the results of multiple trajectories. The information that we definitely have is:

- The current position of the tool in the coordinate system of the serviced object (including orientation parameters);
- Sensitivity to collision with obstacles due to the properties of the receptor geometric model;
- The ability to determine the distances between receptor objects with different codes (but only in the direction of the coordinate axes and in the diagonal directions between them).

Therefore, we will formulate algorithms for constructing the tool path based on heuristic models. The chosen method of forming the tool path among the obstacles is the implementation of the principle of situational management, the methodology of which, however, is designed to solve economic and managerial problems, as well as improve management efficiency. The meaning of situational management is to make managerial decisions as problems arise in accordance with the emerging economic situation [28,29].

Situational theories try to integrate various particular approaches to management. As a result of their development, it became possible to formulate the concept of situational management, the main provisions of which boil down to the following (we describe them as applied only to technical applications):

1. There is no universal approach to management. Different problem situations require different approaches to their resolution.
2. Situational probabilistic factors are taken into account in strategies, structures and processes, as a result of which effective decision making is achieved.
3. There is more than one way to achieve the goal.
4. The results of the same management decisions can be very different from each other.
5. Each situation can be divided into separate elements according to the degree of their influence on the achievement of the main goals and objectives of the organization. These elements are variable and constant.

In our case, the purpose of the operation is to bring the working tool from the starting point to the point of its use, and the distance to the nearest obstacle is the source of information about possible options for movement (at each step towards the target). The capabilities of the receptor method allow you to track distances to obstacles in certain directions. Only in these areas can we send a single “test” receptor in order to determine exactly where it will intersect with the nearest obstacle.

The number of such “location directions” is limited either by the orthogonal direction relative to the coordinate system of the layout space, or by its diagonal direction (Figure 8 a). This limitation of the number of directions is due to the programming feature for setting the movement of the “test receptor” in the receptor matrix relative to the pole of the instrument, indicated in Figure 8 a red dot. Since our receptor matrix is oriented according to the XYZ coordinate system in which the tool pole receptor is selected, the position of the moved “test receptor” is quite accurately controlled by three computational cycles, each of which is capable of “driving” the receptor along one of the coordinate axes - X, Y or Z respectively. The restriction on the “diagonal” movement of the “test receptor” is due only to the desire not to overly complicate the software, limiting the cycle step for each coordinate direction to ± 1. But even with this limitation in Figure 8 a shows that the “direct diagonal” movement
of the “test receptor” in space is possible along 26 axes. Given our desire to move towards a goal, just ahead, we will drop all those directions that do not lead us to the point of use of the tool. In this case, the number of possible directions of movement will be reduced to 17 (Figure 8 b), the distances along which we have to analyze. The analysis will consist in determining the distance to encounter an obstacle when moving in each of these directions. The direction of movement of the “test receptor” to the nearest obstacle is shown in Figure 8 c. Given that the distance will be counted from the tool pole (red dot), then we will need to make an adjustment for the overall dimensions of the tool along one of the axes. To organize the cycle of movement of the “test receptor” in each of these areas, C # language subroutines have been developed. Thus, the procedure for sending a “test receptor” to each of 17 directions will look like:

\[
MoveX \left\{ \begin{array}{c}
 p \\
 0 \\
 0 
\end{array} \right\}, \left\{ \begin{array}{c}
 p \\
 0 \\
 m 
\end{array} \right\}, \left\{ \begin{array}{c}
 p \\
 0 \\
 m 
\end{array} \right\}(R),
\]

Where, \( R \) is the return parameter of the distance to the intersection with the nearest object at a given distance.

Figure 8. Possible directions of movement of the working tool in space.

5. Evaluation of the effectiveness of the model for evaluating the ergonomics of the layout

Heuristic algorithms based on the hierarchy of movements are developed to form the trajectory of the tool moving to the point of using. They stipulate that if a rectilinear movement to the point of using is impossible due to obstacles along this path, then a combination of additional movements and turns of the tool is analyzed in order to “squeeze” it to the point of using we need.

The calculated tool path is determined by a set of discrete tool positions ”from point to point”, a tuple of linear data \((k_1, k_2, \ldots, k_n)\), and a tuple of angular positions at each linear step \((a_1, a_2, \ldots, a_n)\),

\[
\left\{ \begin{array}{c}
 x_i \\
y_i \\
z_i 
\end{array} \right\} - \text{is the three coordinates on each axis at each step}, \quad \left\{ \begin{array}{c}
 \psi_i \\
 \theta_i \\
 \phi_i 
\end{array} \right\} - \text{the three parameters of the angular positions of the tool at each step.}
\]

of the angular positions of the tool at each step. The data on the generated tool path received in C # is written to an external file that can be read in Microsoft Office Excel. An approximate view of the orientation angles when moving the tool to the place of use is shown in Figure 9.

Visualization of the movement of the instrument to the point of use is carried out through the Unity cross platform development environment for computer games. In our case, Unity is used as an engine and visualizer of geometric objects, which has a relatively simple Drag & Drop interface that is easy to configure and debug scenes directly in the editor. The main advantage of Unity in our case is the ability to write scripts in C #.

In the figure 10 shows an approximate graph of CPU time spent on a medium power computer for modeling the movements of various tools to the point of their use. This figure shows that they only
increase slightly depending on the geometric complexity of the shape of the instrument, and in any case much less than the time required to transfer the scene from the solid state model to the receptor one. We see the explanation for this in that the computational operations in the already created receptor matrix, although numerous, are algorithmically homogeneous, which allows for their implementation to get by with data only from the computer's RAM. At the same time, the formation of the receptor matrix itself using the solid state model requires multiple accesses to the macros of the CAD system and connection of the Unity software environment to visualize the result. In addition, the formation of the receptor model of the scene is performed once according to the already prepared solid state model of the object.

Figure 9. An example view of a diagram of orientation angles along the length of movement.

Figure 10. The cost of processor time for the formation of the receptor geometric model of the trajectory of movement of various tools in the service area and the source scene.

6. Conclusions
1. The most important parameter of the ergonomic layout is the ability to mount / disassemble and maintain the installed equipment using various tools.
2. The task of forming the trajectory of movement of mounting tools is very difficult from a geometric point of view and does not lend itself to a rigorous analytical description. The possibility of its solution using receptor (voxel) geometric models and heuristic algorithms for controlling the movement of the instrument is substantiated.
3. The receptor models we use do not use classical 2-valued logic, but 6-valued logic, which simplifies the formation of heuristic algorithms for constructing the path of movement of the mounting tool.

4. The formation of the receptor model of the scene is carried out according to its solid state model of any geometric complexity. This is a relatively lengthy operation (depending on the chosen accuracy of the description of the object - 10 ... 60 min), but performed once. The calculation of the trajectory of movement takes an order of magnitude less time and little depends on the complexity of the geometric shape of the installation tool.

5. The described methodology for assessing the ergonomics of the layout is implemented by joint use of SolidWorks system macros, C# language computing programs and Unity visualization environment.

6. When evaluating the ergonomics of the layout, a number of assumptions were made that simplify the formalization of the task. In particular, when constructing the tool path, the installer’s hands are not taken into account, like physical objects; distance to obstacles is estimated only in orthogonal and diagonal directions, etc.

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