Geometric method for assessing the shadowing of objects in solar power engineering

Leonid V. MARKIN*

*Corresponding author
Department of Engineering Graphics,
Moscow Aviation Institute (National Research University),
4 Volokolamskoe Shosse, 125993, Moscow, Russian Federation,
markinl@list.ru

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Abstract: *This paper describes a geometric model for assessing the effective area of solar panels with regard to their shadowing when the object is illuminated by the solar flow from a given direction. Using energy methods, the flow density, the irradiation created by it, and the exposure in radiant or effective units of measurement were determined. Both physical and mathematical formulation of the problem of assessing the energy efficiency of solar panels using the method of geometric modeling are described. To evaluate energy efficiency, a voxel geometric model was selected that discretizes the computational space. A significant difference in the developed voxel geometric model is that it is multivalued, i.e. uses not a 2-digit, but a 4-digit code. Such ambiguity allows the decisive algorithm to quickly "figure out" the origin of the shadow source when calculating the total effective area of solar panels. The described software implementation of the geometric model, graphical shell, and model verification results can be used in the optimization system for designing spacecraft and other solar energy facilities.*

Key Words: *solar panels, spacecraft, geometric modelling, theory of voxel models*

1. INTRODUCTION

Currently, great attention is paid to the introduction of renewable energy sources around the world. Among them, both for economic and environmental reasons, the first place is occupied by the solar energy. The ecological safety of solar energy and the practical inexhaustibility of the solar resources makes it advisable to widely use solar energy both on Earth and in space exploration to the orbit of Mars [1], [2].

The use of solar energy in space takes on a special role. This is because solar energy in space does not require the delivery of large masses of hydrocarbon fuel and oxygen for its combustion in orbit. In addition, in space there is no energy loss in the atmosphere and dust settling on the panels, which reduces energy production on Earth by up to 40%. This determines the importance and relevance of research in the field of improving the energy efficiency of the use of solar energy on earth and, especially, in space. When designing a spacecraft (SC), the question of assessing the effective area of solar panels arises, considering their inevitable shadowing by each other and other SC structural elements (Fig. 1). All this significantly limits the functionality of the spacecraft.

Fig. 1 – Partial shadowing of solar panels in space at the International Space Station (ISS)

On the ground, to prevent mutual shadowing of the heliostats, they are placed at sufficiently large distances from each other, which requires relatively large tracts of land. Thus, the calculation of the effective area of SC solar panels for any specific orientation of the spacecraft with respect to the solar flow (or static solar cells-heliostats) is an urgent engineering problem.

This paper describes the voxel (receptor) geometric model for assessing the effective area of solar panels, considering their shadowing when the object is illuminated by the solar flow from a given direction, which discretizes the computational space. Both physical and mathematical formulation of the problem of assessing the energy efficiency of solar panels using the method of geometric modeling are described. A significant difference in the developed voxel geometric model is that it is multivalued, i.e. uses not a 2-digit, but a 4-digit code. The results of such a study, implemented in the form of appropriate algorithmic, mathematical and software, help to accelerate the process and improve the design quality of spacecraft and other solar energy systems.

2. MATERIALS AND METHODS

When designing a spacecraft or ground-based solar power plants, we have to decide on the area of solar panels. If there are not enough of them, then the solar energy consumption will be small, if too much, then they will work inefficiently, shadowing each other (not to mention the additional costs for them and increasing the mass of the entire spacecraft). Therefore, the solution to this question can be considered as an optimization problem of mathematical programming.

Put the case that we have a space for placing solar panels (or heliostats) Ω , in which we need to place and orient n solar panels (or heliostats). The set of possible solutions is denoted by X. They are determined by the specific geometry of the SC solar panels and their location relative to the spacecraft itself from the range of permissible solutions Ω. When the spacecraft is oriented relative to the energy flow W (at each time t, each of n solar panels will have an effective energy absorption area $S_i(t)$, and all together at a given time:

$$\mathrm{S}_\Sigma = \sum_{i=1}^{n} S_i(t) \tag{1}$$

Now, our goal is to obtain (i.e., with the given orientation of the spacecraft) the maximum solar energy, determined by the maximum effective area of solar panels, which can be written as:

$$\underset{P_x \to min}{Max}\ S_\Sigma(t)\ \text{for X} \subset \Omega \tag{2}$$

From this expression it follows that the maximum energy should be obtained with additional restrictions – option X for placing heliostats in the region of permissible solutions Ω and minimizing the energy loss P_x, caused by the mutual shadowing of the solar panels by both the solar panels themselves and other SC structural elements. Obviously, the requirement that the X belongs to the region of permissible solutions Ω contains many additional restrictions inside itself – both general (minimizing the occupied area) and specific, caused, for example, by non-planar panels of solar cells, areas occupied by additional power cells on them and not participating in power generation, etc.).

In the case of placing solar panels on inhabited satellites, our mathematical description can be even more complicated by the additional requirement – obtaining maximum energy not at any particular moment, but for the entire time the sun is within the range of its visibility by the heliostat, and obtaining the maximum energy flow $Max\ P_\Sigma$ at a certain time t_0. This is written by the expression:

$$\underset{P_x \to min}{Max}\ P_\Sigma(t)\ \text{for X} \subset \Omega \tag{3}$$

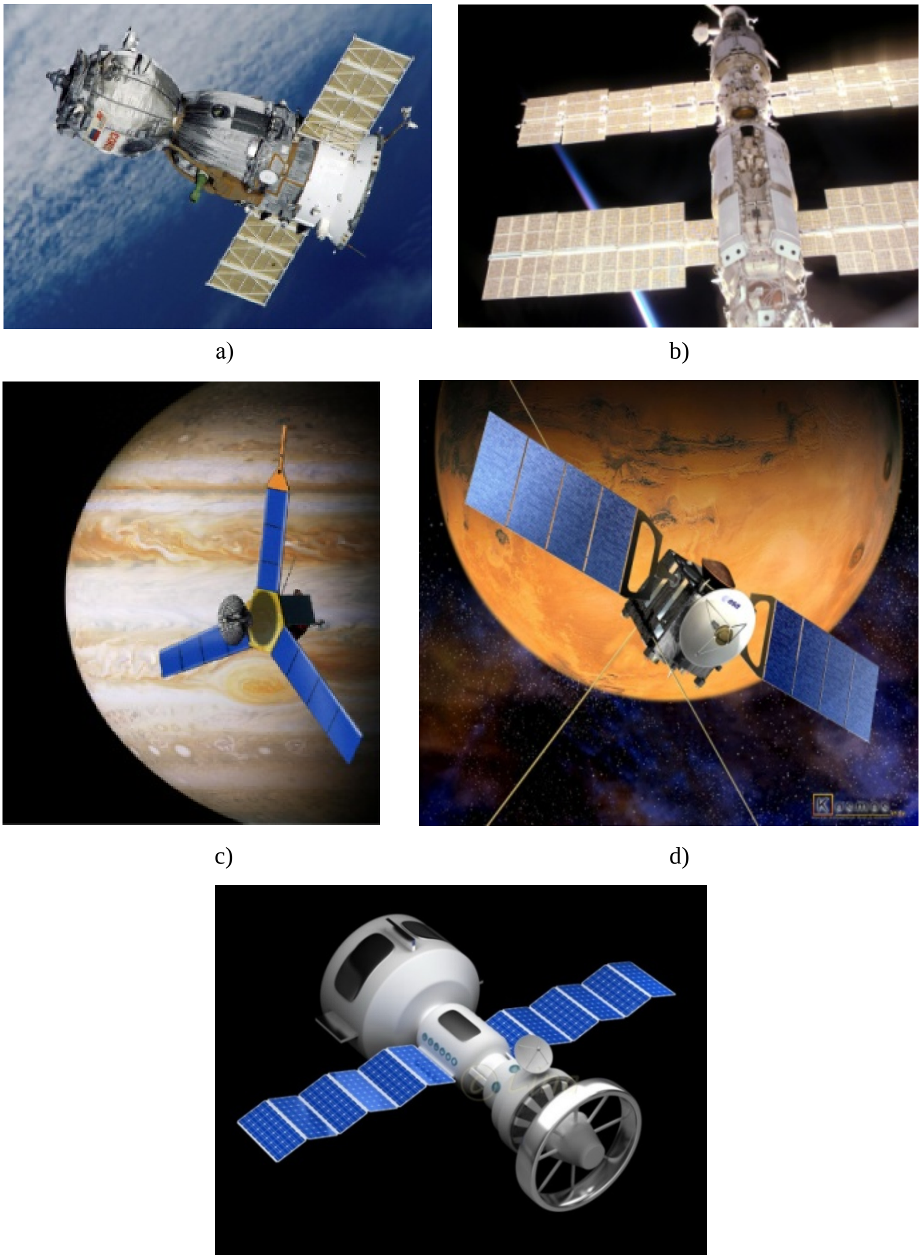
Such a “specific” requirement may be due to the need to require the maximum possible amount of energy for the entire daylight hours at earth-based stations or the time of visibility of the Sun on a spacecraft. Let us try to consider all these factors in our geometric optimization model.

2.1 Known geometric methods for assessing the mutual shadowing of objects

The issues of assessing the mutual shadowing of objects (insolation) have traditionally been addressed in architecture and construction. It is known that the currently used methods of insolation calculations are usually divided into two groups – geometric and energy [3], [4]. Mechanic means of insolation calculations with little accuracy (insolation line, solar protractor, etc.) were developed and widely used. However, even in the 21st century of information technology, descriptive geometry methods form the basis of modern computer algorithms for calculating insolation. Algorithms and computer programs that allow calculating any insolation characteristics have been created.

Energy methods are aimed at calculating directly solar radiation (solar energy) at each moment in time on a site with a certain geographical location. They allow you to determine the flow density, the irradiation and exposure created by it in radiant or effective (light, bactericidal, etc.) units of measurement. Common to both methods of calculating insolation is that to describe the shading objects (as a rule, these are building frame assemblies), high accuracy and detailing are not required. This is precisely what does not allow us to directly apply the described approaches to solving our problem. An additional difficulty in assessing the degree of shadowing of solar panels is that the geometric shape of both the spacecraft itself and its solar panels is extremely diverse.

The geometric forms of spacecraft with their solar panels are incomparably more complicated than the building frame assemblies. The simplest from a structural point of view, linear arrangement of solar panels on the Soyuz spacecraft (Fig. 2a) can be duplicated both in length (on the Rossa spacecraft – Fig. 2b) and in a circular arrangement relative to the central axis (on the Juneau spacecraft – Fig. 2c). If in all previous examples the solar panels were fixed, then on modern SC they can rotate about their axis, as on the European Mars Express spacecraft (Fig. 2d). Solar panels can also be located not in a plane, but at a certain angle relative to each other (Fig. 2e).



a) b)

c) d)

e)

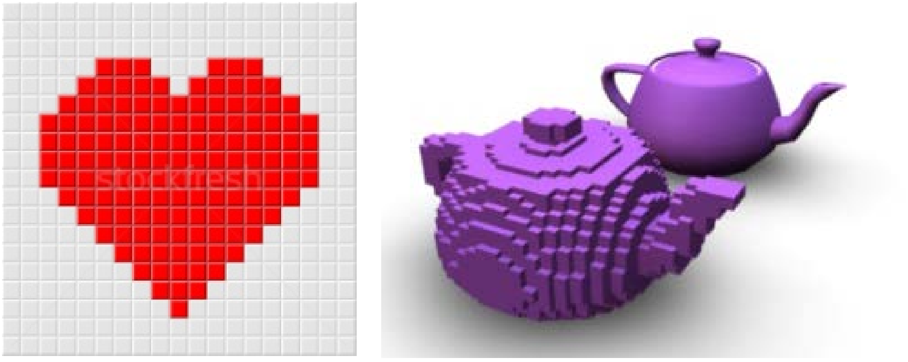
Fig. 2 – Options for the design of the SC solar panels

2.2 Voxel (receptor) geometric models in automated arranging tasks

The problem of determining the influence of objects already placed in space on the passage of sunlight is inherently a geometric problem. Therefore, it is advisable to solve the problem using the method of geometric modeling [5]. Nowadays, the methods of geometric modeling of the external forms of objects have reached a very high degree of perfection and diversity, which allows us to describe almost any geometric shapes with almost any accuracy. However, in our previous works [6], [7] we tried to justify that in some tasks (for example, layout), the accuracy of the description of the object's geometric shape is not the main thing. The other properties of the geometric model are much more important – the possibility of a much simpler determination of the cases of intersection of arranged objects.

Among the vast majority of geometric modeling methods, we will use models that discredit the computational space. It is known that the most accurate formal description of a three-dimensional object as a geometric body is its identification with the space region occupied by it (a point set). However, in such a formulation, the problem of forming a geometric object (GO) can only be considered theoretically. It is possible to use this concept in practice if, as an initial element of the set (E^3), we take not an infinitely small point, but, for example, a cube with dimensions ($l \times l \times l$).The space E^3 in this case is called *discrete* or *voxel*, and the geometric model formed in such a space, respectively, is a *discrete* or *voxel* model.

The English-language analogue of the term "receptor" used in foreign scientific literature is the word "*voxel*" (an abbreviation for the words "VOlumetric" and "piXEL"), i.e. three-dimensional pixel. It should be noted that at present, and in Russian-language literature, this word is increasingly used [4]. We prefer to use the Russian term "receptor", first introduced by the author of this method D. M. Zozulevich [8]. In the literature, the voxel method has other designations ("*matrix*", "*binary*", "*enumeration of space elements*", etc.). A voxel is considered nonexcited if the boundary of the object does not pass through it and it does not belong to the inner region (Fig. 3a). Three-dimensional objects are described by a three-dimensional matrix $A = \{a_{i,}j, k\}$ of dimension $m \times n \times p$ (Fig. 3b).



a) b)

Fig. 3 – a) planar voxel models; b) spatial voxel models

In voxel models, the accuracy of the description of the object's geometric shape, as expected, depends on the discreteness of the voxel matrix chosen by us. Proposed at the beginning of the 70s of the last century by the Belarusian scientist D. M. Zozulevich, this method in those years did not receive distribution due to the limited capabilities of computers of those years. Nowadays, in connection with the development of computing technology productivity, voxel geometric models have found their practical application, including in solving scientific problems [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20]. The voxel method has its own advantages and disadvantages. The obvious disadvantages include the need for large amounts of computer memory for the implementation of such models. However, now increasing this memory to any size is not difficult, either technical or economic. The principal drawback of the voxel model is the impossibility of studying the engineering and differential characteristics of the surface of an object (Fig. 3b). However, this is not necessary for many technical applications.

Another problem is that the constructor never sets the geometry of an object through voxel models. The designer works with a parameter-oriented model containing a description of the type of primitive element and the values of its main parameters, which are easily determined from the drawing. It is parameterization that underlies the work of all modern systems of geometric modeling [21], [22], [23], [24], [25], [26]. Thus, the voxel model can be considered solely as an “intercomputer”. Therefore, there is a need for an additional software module *“Parameter-oriented model”* ↔ *“Voxel model”*. However, methods have now been developed to automatically convert a solid model created in any of CAD systems (for example, in SolidWorks) into a voxel one.

3. RESULTS AND DISCUSSIONS

3.1 Voxel geometric model for assessing the effective area of solar panels

Voxel geometric models do not require complex formulas or logical constructions for their implementation. However, their practical implementation has its own specific complexity. In addition to the need to convert the initial parameter-oriented model specified by the designer into the voxel one, the complexity is due to the need to consider the position and value of each voxel (out of many millions in the voxel matrix), as well as create a mechanism for visualizing the results. MAI graduate student Kui Min Khan (the Republic of the Union of Myanmar) [14] carried out the solution to this problem as part of his thesis research.

An essential feature of our approach is that we will use in calculations not the classical voxel matrix (filled with “0” and “1”), but a multivalued one, in which additional codes will be added. Specifically, it will be three-digit – “0” – free space, “1” – space occupied by the cosmic station, “2” – space occupied by solar cell batteries (Fig. 4).

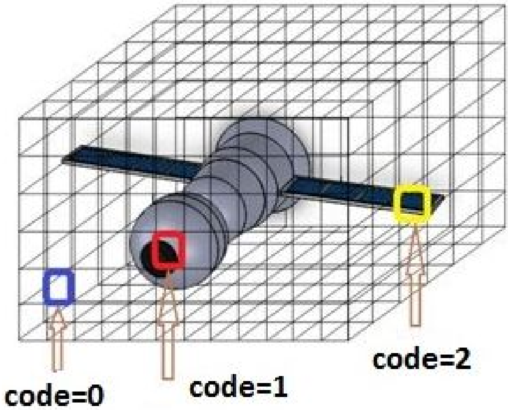
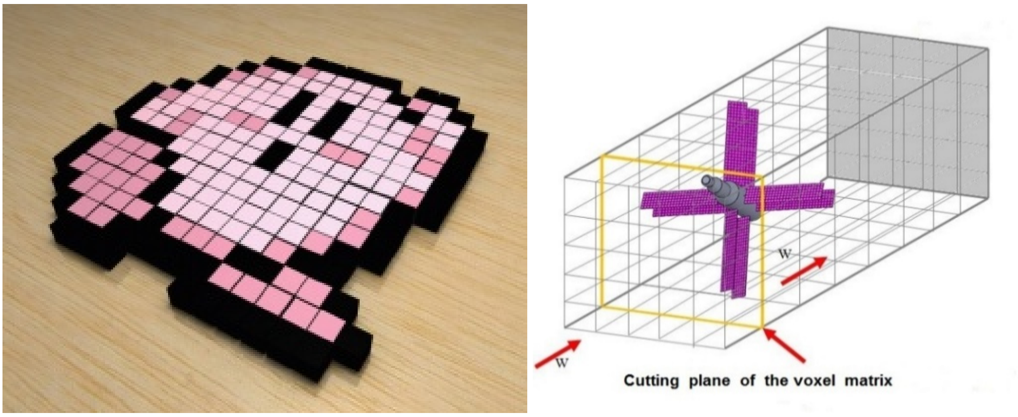


Fig. 4 – Presentation of spacecraft by a multivalued voxel matrix

Using a multivalued voxel geometric model allows you to proceed directly to the calculations of shadowing. We will move the slice of the voxel matrix 1 voxel thick (Fig. 5a) as a cutting plane along the coordinate plane from the beginning to the end of the voxel matrix (Fig. 5b).

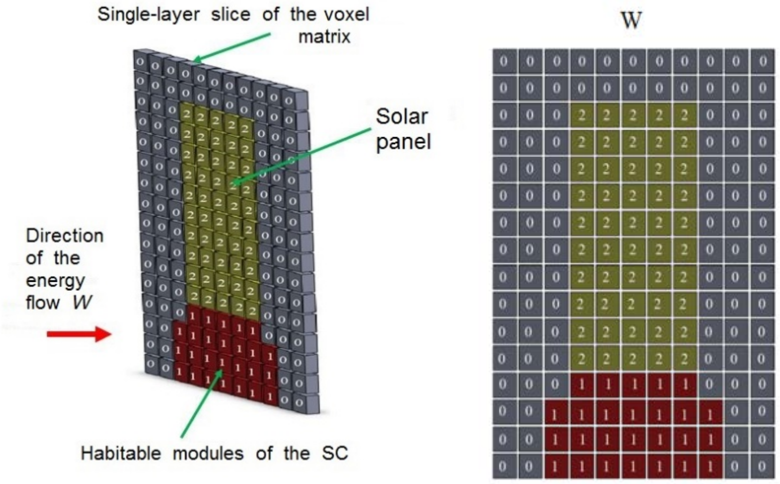


a) b)

Fig. 5 – a) a single-layer slice of the voxel matrix, b) moving this slice along the voxel matrix

In Fig. 6a, we can see that each slice we can assign to each specific voxel either “1” (if it matches the SC body), or “2” (if it matches the solar panels). If there is no match with any SC elements, then the value of the voxel on the slice remains the initially set value of “0”. Looking at the single-layer slice of the voxel matrix from the direction of the energy flow W (Fig. 6b), we see a layer filled with non-zero codes.

It allows us to calculate the total free space area (by the number “0”), the total area occupied by the habitable SC modules (by the number “1”) and, what is most interesting for us, the total area of solar panels (by the number “2”). Further, everything seems to be simple – summing up the area of the voxels with the codes “2” for all slices, we get the region of unshaded areas of solar panels.



0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	2	2	2	2	2	0	0	0
0	0	0	2	2	2	2	2	0	0	0
0	0	0	2	2	2	2	2	0	0	0
0	0	0	2	2	2	2	2	0	0	0
0	0	0	2	2	2	2	2	0	0	0
0	0	0	2	2	2	2	2	0	0	0
0	0	0	2	2	2	2	2	0	0	0
0	0	0	2	2	2	2	2	0	0	0
0	0	0	2	2	2	2	2	0	0	0
0	0	0	2	2	2	2	2	0	0	0
0	0	0	1	1	1	1	1	0	0	0
0	0	1	1	1	1	1	1	1	0	0
0	0	1	1	1	1	1	1	1	0	0
0	0	1	1	1	1	1	1	1	0	0

a) b)

Fig. 6 – a) a single-layer slice of the voxel matrix, b) view of this slice in the direction of flow

In this calculation model, situations are possible where not one but several layers of the voxel matrix (for example, 4 layers) can pass through the thickness of the solar battery, as a result of which the effective area of solar panels will be unreasonably increased by 4 times.

It is also necessary to exclude unreasonable re-registration of already shielded objects. To do this, we will introduce an additional code "3" in the voxel matrix, which will exclude accounting for the areas of the corresponding voxels.

The essence of the model change is that once the absorbed part of the energy flow should no longer be considered.

Therefore, starting from a certain slice of the voxel matrix, everything that follows this slice after the element with the code "2" is forcibly filled with the prohibitory code "3", which does not allow the use of voxels with this code in any calculations.

However, the shadowing of solar panels in the W direction, which reduces their efficiency, is possible not only by other solar panels, but in some cases, by other elements of the spacecraft (for example, by its body).

Therefore, we will make one more change in our model – filling the entire voxel matrix in the W direction with the codes "3" after the first detection on the slice of any SC element.

As in the previous case, the entire remaining part of the voxel matrix in the direction of the energy flow W is filled with codes "3", which excludes the participation of voxels with this code in the procedure for calculating the effective area of solar panels S. Therefore, in a modified (4-digit) voxel model, voxels with code "3" do not participate in any area calculations.

3.2 Software implementation of the geometric model for assessing the effective area of solar panels

Based on the geometric model described above, a software package was created implemented in $C\#$ language, which allows modeling the effective area of solar concentrators.

At the same time, a graphical shell was developed to visualize the calculation process and the calculated parameters of the effective area. The work of the software package is as follows.

After entering information about the geometric dimensions of the station and solar panels (in parametric form), layer-by-layer scanning of sections begins. At the same time, from the 3D matrix into which our entire object (SC) is immersed, a 2D matrix is formed in each layer, the form of which was previously shown in Fig. 5b.

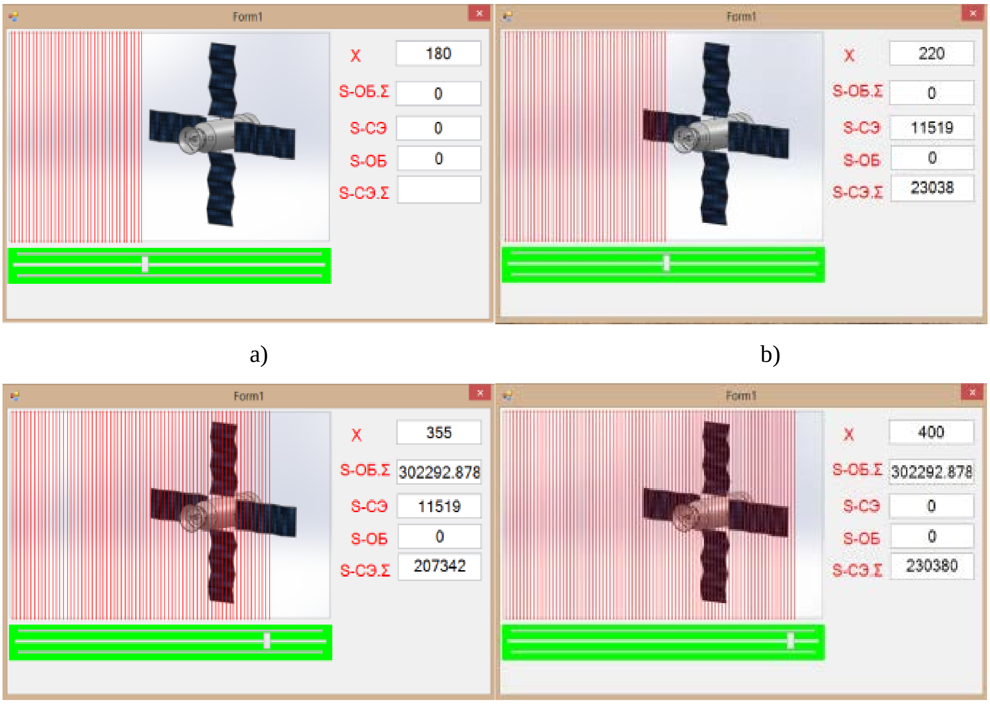
In this case, in each section (slice) of the voxel matrix, the areas of the current section of the solar panels, the effective (accumulated) sectional area of the solar panels and the accumulated sectional area of the space station body are calculated (although this parameter has no practical value for us).

In Fig. 7a it is seen that the cutting plane of the voxel matrix has not yet reached the SC model, therefore all sectional areas are equal to zero.

In Fig. 7b it can be seen that the cutting area passes already along the SC itself, intersecting both the solar panels and the SC body, therefore, in each section of the slice area, specific calculated values are obtained, which are visualized in the corresponding program windows.

Finally, in Fig. 7c it is clear that the cutting plane completely passed through the entire 3D model of the SC, so both the current and accumulated sums of areas in the program windows will no longer change.

Thus, we solved the problem. We determined the total visible area (from a certain angle) of both the space station's body and its solar panels.



X 180
S-ОБ.Σ 0
S-СЭ 0
S-ОБ 0
S-СЭ.Σ

X 220
S-ОБ.Σ 0
S-СЭ 11519
S-ОБ 0
S-СЭ.Σ 23038

a) b)

X 355
S-ОБ.Σ 302292.878
S-СЭ 11519
S-ОБ 0
S-СЭ.Σ 207342

X 400
S-ОБ.Σ 302292.878
S-СЭ 0
S-ОБ 0
S-СЭ.Σ 230380

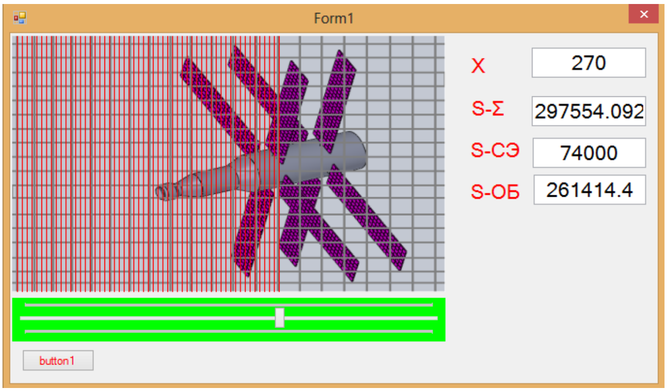
c) d)

Fig. 7 – Stages of scanning a 3D model of a spacecraft of an inclined position for calculating the sectional areas of solar panels and a spacecraft

One of the positive properties of voxel geometric models is the ability to quickly calculate the sums of voxel values.

Having at each slice a planar voxel matrix of the type depicted in Fig. 6b, we can calculate the total value of "twos" and thereby the effective area of solar planes for a particular spacecraft geometry with its specific orientation relative to the direction of the solar energy flow.

An example of a program in *C#* for obliquely oriented spacecraft for SC with a more complex geometry of solar panels is shown in Fig. 8. This figure shows the calculation results as the cutting plane moves along the matrix slice.



X 270
S-Σ 297554.092
S-СЭ 74000
S-ОБ 261414.4

Fig. 8 – The calculation of the SC effective area in its arbitrary position relative to the direction of sunlight

3.3 Assessing the accuracy and efficiency of the geometric model of the degree of shadowiness of SC solar panels

To assess the accuracy of the implementation, we will study the test model of the spacecraft, the geometric parameters of which allow us to determine in advance the value of the effective area of solar panels. This will allow us to “run” this model through a geometric model implemented in $C\#$ with previously known parameters of the effective illuminated area. So, the results of calculating the area for the test spacecraft with the previously known theoretical values of S (the effective (unshaded) surface of the SC solar panels) are shown in Fig. 9.

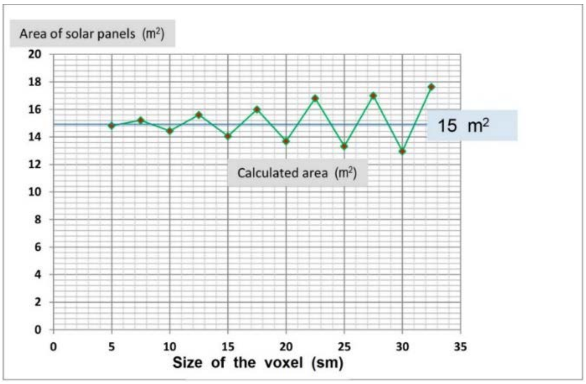


Fig. 9 – The calculated values of the solar panels area in the test example (for the area $S = 15\ \mathrm{m}^2$)

Figure 9 shows that the regression curve does not leave the theoretical area of solar panels, which indicates the correctness of our geometric model. With an increase in voxel size, the calculated value of the effective area deviates more and more significantly from the theoretical value, which is quite expected. We have no explanation for the fact that the calculated values are strangely arranged in such a symmetrical way to the theoretical curve with nominal values. Apparently, this is due to the predetermination of the discrete algorithm for calculating the effective area of solar panels.

From the theory of voxel models, it is known that for increasing the accuracy of calculations by reducing the size you have to sacrifice the time of calculations (which, however, is obvious). The results of comparing the accuracy and calculation time (process time) are presented in Fig. 10. It should be noted that a personal computer (PC) with performance characteristics slightly above average was used for the calculations.

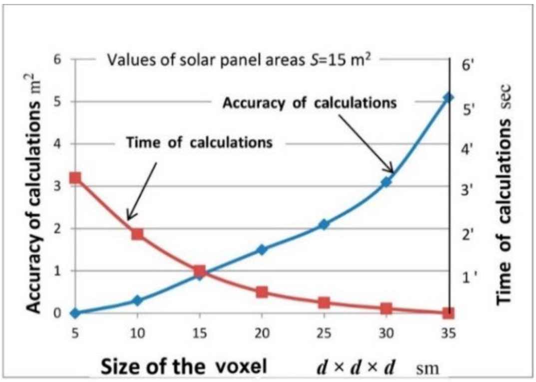


Fig. 10 – Dependences of the calculated values of the error in the areas of the test example and process time of calculations on the size of the voxel for $S = 15\ \mathrm{m}^2$

The results obtained indicate that by reducing the size of the voxels, high accuracy can be achieved without a significant increase in process time for calculations. It can be seen from this figure that with a linear voxel size of 5 cm, the error in calculating the effective area was $0.3\ \mathrm{m}^2$ with a theoretical total area of solar panels of $15\ \mathrm{m}^2$. The calculation error in this case is 2% with a process calculation time of 3.2 seconds, which is a quite acceptable result for practice. Apparently, such a small process time is explained by the homogeneity of the computational operations performed by a modern PC using only random-access memory (without accessing the disk storage during calculations).

Obviously, not all ways to reduce process time for the computer implementation of our geometric model were involved and we see other ways to reduce it (or to increase the accuracy of the results with the same time costs). However, the results already obtained on the calculation time (less than 10 seconds of process time) and on the accuracy of the calculation of the result (tenths of a percent) according to experts can be considered quite acceptable for practical use.

4. CONCLUSIONS

Thus, the study allows us to draw the following conclusions:

– the problem of assessing the effective area of solar panels, being a classic arrangement task, is solved by geometric modeling methods;

– geometric placement problems, due to their specificity, are conceived to require the use of non-traditional geometric models, in which the accuracy of the description of the shape of objects is sacrificed to other indicators of model efficiency. Such “effective models in their own way” with good reason include the receptor (voxel) geometric models;

– verification of voxel models for accuracy and performance showed their ability to solve problems with accuracy acceptable for practice in a short time (up to 10 seconds);

Currently, the use of voxel models is limited by the complexity of preparing for calculation of the voxel models themselves and the complexity of their visualization in modern computer graphics systems. However, ways to overcome these difficulties are identified. A cardinal solution to this problem would be to create an additional interface between voxel geometric models and common CAD – systems (SolidWorks, AutoCAD, COMPASS, etc.); the voxel geometric model for assessing the effective area of solar panels described in this article can be used as a calculation module in the system for optimizing the design of spacecraft and solar energy facilities.

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