Method of formalizing the layout of the internal compartments of aircraft

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DOI: 10.13111/2066-8201.2019.11.S.14

Received: 30 April 2019/ Accepted: 07 June 2019/ Published: August 2019

Abstract: *The mathematical formulation of the aircraft's internal layout problem is described as an optimization problem, with an indication of its objective function, constraints, and performance criteria. The approach (receptor methods and apparatus of normal equations) is justified, which makes it possible to move from enumeration method of placing added objects to intelligent algorithms of automated placement when creating geometric models of automated layout. It was shown that preparing the aircraft for layout automation complicates the mathematical description of geometric models of added objects, increases the complexity of their visualization in modern computer graphics systems and makes the need to create an additional interface between new geometric models and common CAD systems (SolidWorks, AutoCAD, COMPAS, etc.).*

Key Words: *automation, layout, internal compartment, aircraft, geometric models; conditions of mutual intersection.*

1. INTRODUCTION

When designing aircraft, the genius of the General Designer has a very important role. Their names are written in history (Tupolev, Yakovlev, Boeing, Douglas, etc.) and became nominal. If at the dawn of aviation design there was a lot of geniuses of individuals, now many thousands of design bureaus are engaged in this. The design assignment is decomposed both structurally and procedurally. And we must pay tribute to the fact that the tasks of aerodynamic, strength analysis are very well solved. Difficulties in formalization are facing problems of synthesis. Most projects operate on prototypes. Often the optimal solution is not sought, but is limited to some rational, which is obtained in a limited time. New information technologies presented project-designers ample opportunities for solid-state, hybrid and parametric geometric modeling, and CAD analysis (SolidWorks, AutoCAD, COMPASS, etc.).

The objectives of the synthesis of structural layout solutions are very difficult to formalize. In addition to the graph-analytical presentation, this type of tasks is characterized by a semantic representation and is realized through matrix-topological methods. The most challenging of the problems of synthesis is the task of composition. Layout problems arise on all design stages of aircraft [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12]. They are divided into external and internal. The triple problem of aerodynamic, volume-weight and structural-power layout of units and systems is usually solved [1], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29]. It is very significant to develop an approach that will allow to formalize the internal layout of the units and systems, which will allow at the next levels to complete the formation of the appearance of aircraft variants in an automated manner.

2. METHODOLOGY

From a math point of view, the problem of placing geometric objects can be formulated as an optimization problem of the following form [1]. Let there be *N* added objects $T_i(i = 1, ..., N)$ and the allocation area Ω. It is required to place these objects minding Ω limitations in such a manner that the objective function layout *F(x)* reaches an extremum, i.e., define

$$Extr\ F(X) \text{ at } X \subset \Omega \,, \tag{1}$$

where *X* is a variable that determines the location parameters.

Hence, the mathematical formulation of the allocation problem includes 3 components:

1) The choice of the function for the objective *F(X).*

2) Variable *X* selection.

3) Selection and formalization of limitations.

Basic geometric condition of rational allocation of objects is a condition of rational placement in an area Ω of some set of Composites Objects $\{T_i\}_1^n$ (where *n* is large enough) or the largest number of groups of objects $\{\{T_i\}_1^n\}_1^m$ (where *m* large enough). In this case, we have to talk about rational, and not about the optimal placement of objects, because into force Astronomical number of layout options (its multi-variant) achieving global extremes of a function layout purpose is virtually eliminated. Placing added objects can be done under the following conditions imposed on the area of placements

1) The area Ω has the specified form and size.

2) The region Ω has moving limitations.

In practice the compositions of real technical objects are realized through first condition in the layout area Ω (second condition is typical for the case management of cutting material), so in all cases, we will consider area Ω with fixed limitations. Apparently, in terms of geometric basic criterion is to optimize the placement in the space the fill factor is K_V. The coefficient K_V (sometimes called the density coefficient of the composition) is the ratio

$$K_V = \sum_{i=1}^{n} V_{v.c.} / V_{comp.} \tag{2}$$

where $\sum_{i=1}^{n} V_{v.c.}$ – the sum of the volumes n of the arranged objects,

V_{omc} – the volume of the compartment in which the layout is made.

The condition for maximum build density is recorded as

$$\frac{Extr\ V(X)}{Kv^{\to 1}}\ at\ X \subset \Omega \tag{3}$$

Expression (5) is trying to have content objects settled in a volume closer to total volume of the compartment, however, is not the most convenient for further calculations. Therefore, further detailing of expression (3), which is necessary for optimization by K_V, is the transition from minimization by volume to minimization by distance between objects. Optimization by K_V is achieved by the most compact (ideally – dense) placement of added objects, the fundamental concept of which was introduced by Yu. G. Stoyan and N. I. Gil [23]. Let's remind that added objects T_1 and T_2 (the position area can be used as one of them (they are densely located along the $\rho_{1.2}$ direction (Fig. 1), if the distance between them $\rho_{1,2}(T_1, T_2) = 0$. Thus, the compact placement condition can be written as

$$\forall T_{i,j}\left[T_{i,j} \in \{\{T\}_1^n\}_1^m \rightarrow \rho_{i,j}(T_i, T_j) \rightarrow \min\right] \quad (4)$$

i. e. the distance between all added objects should be minimal.

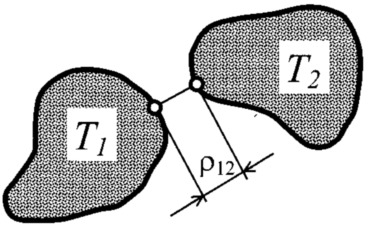


Fig. 1 – Minimum distance ρ_{12} between the placed objects

It would be a noteworthy simplification to assume that the maximum placement density is the only criterion of layout efficiency – everything is much more complicated in life – many other requirements have to be taken into account – given alignment, ease of maintenance, mutual compatibility of objects, etc., but in this article we will limit our attention to only purely geometric placement requirements.

The second geometrical condition for optimizing the location is a mathematical notation ensuring the condition of mutual non-intersection (CMNI) of the objects being assembled, which is written as

$$\forall T_{i,j}\left[T_{i,j} \in \{\{T\}_1^n\}_1^m \rightarrow T_i \cap T_j \rightarrow \emptyset\right] \quad (5)$$

i. e. the intersection of any added objects between them forms an empty array.

The third condition for optimization specific to the design of the aircraft, is to minimize the weight of arranged objects and connections among them, which can be written in this form:

$$Extr\ \sum_{i=1}^{N} M_i\ (X) \qquad at\ X \epsilon \Omega, \quad (6)$$

where $\sum_{i=1}^{N} M_i$ – is the entire mass of the assembled objects and communications among them, as well as centering loads.

3. RESULTS

Naturally, the total mass of the assembled objects remains constant for at any value of the parameter X location , therefore minimizing the total mass $\sum_{i=1}^{N} M_i$ is achieved in the following ways:

1. *Minimizing weight of communications that are arranged between objects* (mass Communications in AC reaches 40% of the mass of added objects [6], [7], [8], [9], [13], [14], [15]. This condition can be represented in the following way:

$$Extr\ M_k\left(\{\{T_i\}_1^n\}_1^m, X = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{p} S_k L_k\right), \quad (7)$$

where M_k – is the mass of communications among the set of objects, p – the number of k communications types, S_k is specific (linear) mass of communications $\hat{e}$ – type, L_k – the span of the communication k – type.

2. *Providing with the layout of the specified centering of the aircraft compartment*

The condition for ensuring a given centering is formalized as follows. The real position of the center of mass (CM) N assembled objects in the AC coordinate system is determined by the relations

$$x_A = \frac{\sum_{i=1}^{N} x_i m_i}{\sum_{i=1}^{N} m_i}; \quad y_A = \frac{\sum_{i=1}^{N} y_i m_i}{\sum_{i=1}^{N} m_i}; \quad z_A = \frac{\sum_{i=1}^{N} z_i m_i}{\sum_{i=1}^{N} m_i}. \tag{8}$$

where $A(x_A, y_A, z_A)$ is the real position of the CM of the aircraft compartment, m_i is the mass of the i-th assembled object.

The specified position of the center of mass is given by a certain point $B(x_B, y_B, z_B)$. The alignment is considered to be provided if the distance between points A and B does not exceed a certain technical specification of the value ρ_{AB} i.e. the actual position of the CM is in the sphere or ellipsoid of the allowed positions of the CM. In the event that this condition is not fulfilled, it is necessary to install additional centering weights in the compartment, which are for us represent a "fine" by weight that we have to pay for the unsuccessful (in terms of alignment) layout of the compartment. When installing centering masses to point $C(x_C, y_C, z_C)$, the weight of the balancing weight $M_б$ provides the specified position of the CM Inc. $B(x_B, y_B, z_B)$ determined by expression:

$$M_c = \frac{\sum_{i=1}^{N} m_i x_c - x_B \sum_{i=1}^{N} m_i}{x_B - x_C} + \frac{\sum_{i=1}^{N} m_i y_C - y_B \sum_{i=1}^{N} m_C}{y_B - y_C} + \frac{\sum_{i=1}^{N} m_i z_c - y_C \sum_{i=1}^{N} m_i}{z_B - z_C} \tag{9}$$

For certain kinds of aircraft in addition to the restrictions on the position of the CM there are constraints on the moments of inertia. Most widespread is the requirement for the moments of inertia around the axes Ox and Oy in the Cartesian coordinate system $Oxyz$ expressed by the relationship:

$$\sum_{i=1}^{N} \left[m_i (y_i - z_i) + \left(J_{zi} - J_{yi} \right) \right] = 0, \tag{10}$$

where x_i, y_i, z_i – coordinates of the CM of the i -th compiled object, J_{zi}, J_{yi} – own inertia moments of *i-th* arranging the anterior object.

Installed to comply with this requirement to the point $D(x_D, y_D, z_D)$ balancing mass will be equal to

$$m_{c.i.} = \frac{\sum_{i=1}^{N} m_i (y_i^2 - z_i^2) + \left(J_{zi} - J_{yi} \right)}{z_D^2 - z_D^2} \tag{11}$$

In some (quite rare) cases, restrictions are enforced on the centrifugal moments of inertia, which should not exceed the tolerance for the sum of centrifugal moments of inertia:

$$\varepsilon_y \geq \left| \sum_{i=1}^{N} m_i x_i y_i \right| + \left| \sum_{i=1}^{N} m_i y_i z_i \right| + \left| \sum_{i=1}^{N} m_i z_i x_i \right| \tag{12}$$

Compliance with this condition will also require the installation of an additional balancing weight mass. $\Delta M \delta$.

Expression, to determine guides value $M \Delta \delta$ depending on the point of installation and other conditions are too complicated, whereby we omit them completely, and refer to a detailed description or their operation[19].

In addition to minimizing the mass of the design, which is the main optimization criterion for aircraft layout, there are other, additional optimization criteria, which include:

3. *Ensuring a given reliability of the aircraft units.*

The demand to ensure the reliability of the operation of assembled elements is formalized as the need to obtain the actual reliability $P_ô$ exceeding the calculated lower-permissible reliability, i.e. $R_f \geq P_p$ for any set of equipment (in suggested independence of each of the N individual components of the equipment and the lack of redundancy) reliability of complex is determined by ratio

$$P_f = \prod_{i=1}^{N} P_i \tag{13}$$

where P_i is the real reliability of each component, defined in

$$P_i = P_{pi} \cdot K_i(x_i, y_i, z_i), \tag{14}$$

where P_{pi} – estimated reliability i th component; K_i – is coefficient of reliability decrease at the compartment point with coordinates (x_i, y_i, z_i) determined by the physical parameters of the compartment at this point (level of vibrations and mechanical overloads, temperature, humidity, etc.)

The value of the coefficient K_i varies from 0 to 1 and is determined experimentally. Considering the extreme complexity and laboriousness of work on the determination of the coefficient K_i for all components of the onboard aircraft systems, carrying out layout calculations by this criterion of optimality is not presently possible.

4. *Reducing labor costs for installation and maintenance of assembled objects*

These labor costs are constituted not so much by the position of the assembled objects in space, as by their relative position relative to the operational hatches and other arranged objects, which hinder their installation and maintenance. These labor costs in the form of unit costs $\mu_{l.m.}$ can be described by the relation

$$\begin{aligned}\mu_{l.m.} = (x_1, \cdots, x_n, y_1, \cdots, y_n, z_1, \cdots z_n) = \frac{1}{T_{op.}} \sum_{i=1}^{n} [S_m(T_{op.}) \cdot C_i^s(x_i, y_i, z_i) +] \\ + K(T_{op.}) \cdot C_i^k(x_i, y_i, z_i) + M(T_{op.}) C_i^m(x_i, y_i, z_i) + \cdots],\end{aligned} \tag{15}$$

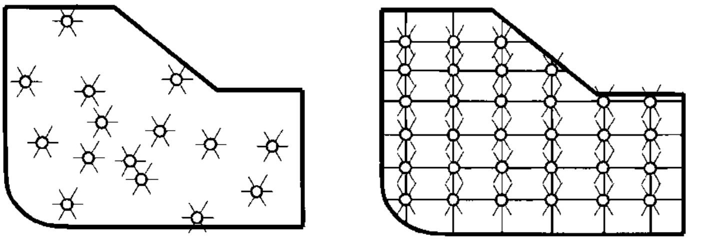
where C_i^k – labor costs for dismantling and installation work when servicing the i – th block; $S(T_{op.}), K(T_{op.}), M(T_{op.})$ – the number of S, K and m services during the operation interval.

The study of this optimization criterion as the main one is advisable only for a very specific class of aircraft. Hence, this optimization criterion (as well as the previous one), as a rule, appears in layout as constraints on layout solutions. Essentially new layout capabilities have emerged when using computer-based solid-state modeling methods that allow not only creating virtual layout models, but also with high accuracy to check for them possible cases of mutual intersection of added objects. However, even these advanced design and computer modeling methods analyze only the existing structure, the elements of which are obtained by the designer using a small set of typical operations (extrusion, extrusion along a trajectory, rotation, modeling over sections, deformations), which does not allow modeling the most complex “sculptural” objects., and for objects of simpler forms does not guarantee optimal design. Thus, a virtual model of a technical object created in any system of geometric modeling (SGM) is nothing more than a specific design of a technical object realized by the SGM, taking into account the personal experience of the designer (not the fact that it is the best).

As stated above, modern methods of geometric modeling allow analytic to describe geometric forms of almost any degree of complexity, but this does not bring us closer to the problem of computer automated layout, for which it is not the accuracy of the description that is more important, but other specific properties of the geometric model:

- The aptitude to relatively simply determine cases of mutual intersection of the arranged objects;
- The aptitude to generate algorithms for rational placement of an object in space based on this model.

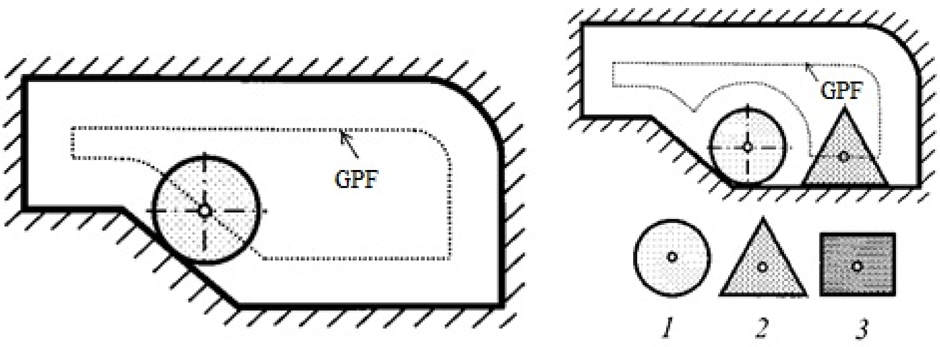
Even if we had a mathematical apparatus that allowed us to determine the shortest distance ρ_{12} between already placed objects, we would not come close to solving the problem of how to rationally arrange them. The simplest models of automated location of geometric objects are shown in Figure 2 (to simplify perception, only a flat version is illustrated).



a) b)

Fig. 2 – Geometric models of object placement: a – randomly; b – on a regular grid

Presented in Figure 2*a* is the method includes placing randomly chaotically spreading objects within the given space (e.g., via a random number generator), followed by a test of this embodiment, the layout on condition no mutual intersection (CMNI), and other layout quality criteria. Placing on a regular grid provides for the sequential movement of objects at specific fixed points and an assessment of the quality of the layout in each of them. It should be noted that no one has the illusion that not only the optimal, but even more or less acceptable layout solution will be found in this way – a subsequent test on the CMNI immediately breaks these hopes. Geometric models of CMNI is a topic for a separate, very difficult conversation with the reader. If, however, everything has been done with the CMNI, then the next object to be placed is selected and everything starts all over again. You need a lot of searches in order to reach at least some sort of position option that does not contradict common sense. All parameters of this placement are remembered (location of objects and efficiency coefficient) and compared with the previous saved one (if it exists). If the current version is better than the previous one, then the previous one is forgotten, if it is worse, then the current one is forgotten. At the same time, we keep the so-called record value of the layout parameters (although in practice they retain a few – for example, the 3 best ones). It would seem that the solution of this difficult problem was suggested by representatives of the Ukrainian scientific school Yu. G. Stoyan and N. I. Gil, the hodograph of the dense placement function (GPF) [23]. Geometric interpretation of this method is shown in Figure 3*a*. GPF – is the trajectory of the object is placed at each point where it remains firmly – placed in relation to the closed area. The fixation of an object to be placed at any point, by definition, ensures the fulfillment of the CMNI and is allowed. The question arises – and at what specific point of the GPF should we stop if they are all equally valid? Here we need to adopt some additional decision rule – for example, that the fixation point must be a path point with a minimum value of the *x* and *y* coordinates (Figure 3*b*).



a) *b)*

Fig. 3 – Placement of the object using the hodograph of the dense placement function (GPF): *a* – the placement of the first object; *b* – placement of subsequent objects

The object placed in such a way becomes the prohibition area itself and for the next object to be placed (object 2 in Figure 3*b*) a hodograph is made taking into account the object already placed 1. And so on until we place all the objects we have. It would seem this way all problems are solved with the location of the object, and with the CMNI with areas of prohibition and other objects. But not everything is so simple:

– the construction of a GPF for complex spatial objects (their actual spatial equidistant) is an extremely hard, sometimes unsolvable, geometric problem;

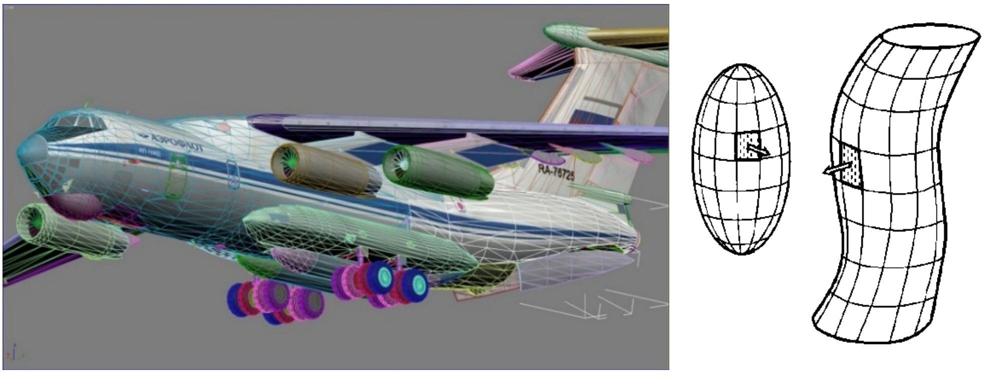
– the issue of choosing the location of the object within the GPF on other layout criteria (for example, alignment) remains unresolved;

– a big problem is the choice of a sequence of objects to be placed. In the language of geometry, this is called “the permutation space metrization”. It is clear that for *N* placed objects it is necessary to build *N*! (factorial) very difficult functions of possible paths.

From the preceding it is clear that even here we did not manage to get away from the brute force, and the method of GPF, which works effectively in flat cutting tasks, turns out to be a “medicine worse than the disease” for complex spatial arrangements. And this is despite the fact that we abandoned one more parameter – the angle of rotation φ οφ τηε object around its axis in the process of placement, which would sharply increase both the complexity of constructing the GPF and the number of possible choices.

It is for these considerations that the task of automating the placement does not seem to have an unambiguous solution algorithm that is effective for all types of layout tasks [22]. Therefore, in the well-known methods of solving problems of placing objects while keeping in mind the absence of intuition in a computer, it is replaced by a “blind search” for the layout option. To our deep regret, such a “brute force search” is beyond the power of even modern computers, whose computational capabilities appear inexhaustible to us. And one more question that seems fundamental to us is about the degree of automation in solving computerized placement tasks. There are *automatic* layout methods in which we get at the output a ready-made, computer-generated layout solution, and *automated* methods that not only do not exclude, but, on the contrary, infer the active involvement of the designer in the process of obtaining a solution. It seems to us that in the foreseeable future, it will not be possible to accomplish the solution of this complex problem using purely reordered placement algorithms and the ideas being developed, and the methods should provide for the designer the ability to influence the result obtained by cutting off the apparently inefficient and inefficient layout solutions.

At the current stage of development of technology, this is exactly what is happening. The designer, by his own understanding, interactively places the objects in any CAD system, and asks it to determine if there is an intersection of the placed objects. Such a calculation occurs within the system and is illustrated schematically in Figure 4 .The system divides the surface of the object into individual elementary screened plane parts (facets – Figure 4*a)* and the known formulas from analytic geometry checks their suppression or mutual distance from each other (Figure 4*b)*.It is clear that there are some exhaustive search algorithms here, but each company – a developer of CAD systems – has its own "know-how" – proprietary algorithms that optimize this process. The great benefit of this method is the fact that many of the standard operations of this method were able to be transferred to the hardware level and put into execution for the computer's graphics accelerator.



a) b)

Fig. 4 – Illustration of the method for determining CMNI in modern CAD systems

The use of the apparatus of normal equations in the tasks of automated layout is extremely interesting – such an object, as it were, itself determines the distance and direction to the point of interest. Hence, algorithms based on the use of this method acquire elements of artificial intelligence, which determines the rational direction of movement of an object to obtain the densest layout. The algorithm itself determines the minimum distance to another added object and the direction in which it should move before contact with this object.

Though such approaches open up new possibilities for creating intelligent compositional algorithms [1], [18], [19], [20], [29], the authors do not need to use the "blind search" to realize that the practical implementation of these approaches requires the association of appropriate software to standard geometric modeling systems as additional calculation modules.

4. CONCLUSIONS

1. The process of constantly increasing the power of computers and their applications permits us to hope that geometric methods for describing geometric models of added objects using receptor geometric models and normal equations and receptor methods will take their place along with many other types of geometric models that are now perceived as classical.
2. By means of the apparatus of normal equations in the tasks of automated layout acquires elements of artificial intelligence, when the algorithm of the method by itself determines the distance and direction to the point of interest to us.
3. For the practical implementation of the inner layout approach, it is necessary to link the appropriate software to standard geometric modeling systems in the form of additional computational modules.

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