Adaptive imaging system for electromagnetic scattering field of aircraft

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Abstract. Electromagnetic compatibility (EMS) of a sophisticated aircraft technical system with other systems is a prerequisite for their sustainable operation. Aerospace technology, where both highly sensitive measurements and energetic control effects are closely combined in the dense layout of an aircraft, requires a solution to the EMS problem. This paper shows the need for effective technology to control the electromagnetic radiation created in the surrounding space, both by subsystems of aircraft and by the whole object. The method how to visualize of 3D electromagnetic field both in space and in time is considered.

1. Introduction
Electronic devices have become an integral part of human life and any technical system, that has interactive properties and requires certain conditions for sustainable functioning. One of these mandatory conditions is EMS [1] of the entire system and its subsystems with each other, there are no less complex and sensitive. Although digital technology is fundamentally highly disruptive, but the modern technical system contains a number of analog sensors, communication lines, receiving antennas, which are sensitive to the external interfering signals both through wires and the air. Hence, the problem of EMS is relevance for integrated technical systems, that perform of measuring, data processing or control commands creating either digital or analog. One example is aerospace technology, where highly sensitive measurements and energetic control influences are closely combined in a dense aircraft layout. EMS of such systems are being provided at all stages of the aircraft lifetime, from development, to stand-up tests, including operational phases. EMS tools [2] are screening, time and frequency separation, minimizing of cross-influence by means of design and circuitry methods, with objective visualization of their results. To quantify the EMS of the aircraft, an effective technology is needed to control the electromagnetic radiation fields, generated by both individual subsystems and the whole object. It is shown that existing imaging methods do not provide to select the observation plane in the 3D-space of the observation zone, as well as organize a visual 3D visualization of the scattering field spatial distribution around the object. The aim of this work is to formulate proposals for the spatial distribution visualizing of physical fields for different applications. The work proposes a system of assessment of external electromagnetic radiation of an aviation, which built on mapping the radiation field in a limited observation zone on a given 3D grid [3]. It is proposed an algorithm for measurement results imaging by either brightness changing of markers, and in a given a priori color scale. The problems of in time animation, imaging of measured values and spatial visualization have been solved.
2. Background definitions

2.1. Definition of Visualization

Popular Wikipedia [4] defines the visualization procedure as a method of presenting information in a visual form, in a form, suitable for studying with the help of the human eye. Everyone knows the visualization of the magnetic field with iron sawdust, or visualization of the flow of liquid or gas by injecting them with contrasting substances (smoke in the gas, bubbles in the liquid). Visualization of the electromagnetic field in our task involves discretizing of the field in the nodes of a 3D grid with a cubic shape.

2.2. Overview of experimental data visualization techniques

The visual representation of the results has always been of interest as a final phase of any study, answering the question of the size and nature of the measured or calculated value. Oscillographs [5] have been a means of measurable values visualizing up to units of seconds duration, in the very recent past. Also the recorders [7] were widely used, which used, with record by "ink" on the paper. Visualization of fast and long processes in a wide range with simultaneous registration became possible only as a result of the computers with advanced software. Popular MatLab and MathCad computing packages have advanced imaging tools for calculating results, both in the form of 3D spatial imaging and multi-channel time dependencies. However, these packages are off-line applications, and their alignment with real-time systems causes a number of difficulties, which were not provided by these data computational tools. Advanced computer imaging programs are represented by universal products [8–10] such as Google Data Studio etc. These products are widely being used in business analytics, logistics and allow to give a visual view of the calculation data in the form of charts, functional graphs and reports. Attention is paid here to the order of information placement, the creation of visual images. That helps an analyst or manager to make the right decisions by identifying trends and calculating statistical estimates, based on the available information. However, in scientific tasks, these software products have limited application, as they do not allow to carry out spatial 3D visualization, they work in off-line mode, having no connection with the external interface, and do not display 3D processes in real time. Besides, the developer of these tools does not give Software Development Kit, which limits the possibilities of their application.

3. Software creation methodology

3.1. Determining the number and position of the settlement grid nodes

It is proposed the equidistant position of the grid nodes in the space of the cubic form observation zone, which allows to attribute the calculated or measured values of inductions of fields [11–14] to specific points of space, surrounding the study object. The coordinates of the control grid nodes are a parameter, that allows to quantify and link the electromagnetic field induction to the object coordinate system. The 3D grid from the checkpoints in the nodes fits into the observation zone. The number of dots on one side of the controlled zone is indicated by the natural digit, making it easy to change the size and detail of the visualization system in question at the software level. The number PPC points, located on an arbitrary selected section of the observation plane, as shown in Figure 1, is determined by the formula:

\[ PPC = R^2, \]  

(1)

where: \( R \) — the number of points on one of the axes of the chosen plane.

The total number of points in the specified volume can be calculated by the formula:

\[ PC = R^3, \]  

(2)
The numbering of the points begins at the bottom left rear edge of the volume with the rectangular Descartes coordinate system, i.e. at \(X < 0, Y < 0, Z < 0\), and continues first on the X axis, then on the Y and Z with increment \(PS\), calculated by formula:

\[
PS = \frac{V}{R - 1},
\]  

where: \(V\) — the volume of the calculated cube \([m^3]\).

\[ (3) \]

**Figure 1.** Point on the plane: (a) — promising view; (b) — side view.

The position of each settlement point on the X, Y and Z axes can be calculated by formulas:

\[
PX = MOD(I, R) \times PS - \frac{V}{2},
\]  

\[ (4) \]

\[
PY = MOD\left(\frac{I}{R}, R\right) \times PS - \frac{V}{2},
\]  

\[ (5) \]

\[
PZ = \frac{I}{PPC} \times PS - \frac{V}{2},
\]  

\[ (6) \]

where: \(MOD\) — the result of dividing with the balance of the first argument for the second, \(I\) — the index (number) of the settlement point. This technique is operating equally well in both the right-hand and left-hand coordinate system, but we will use a traditional left-handed system in this paper. Using formulas (1–6) it can generate a 3D cube of settlement points, as shown in Figure 2 (a), which will link the results of measurements to a specific system of coordinates of the observation object. The numbering of the calculation points of the cubic settlement grid with a resolution of 3 points on the side is shown in Figure 2 (b). The cube grid, which contains 7 points on each side, is shown in Figure 2 (c). Measurements in the nodes of the calculation grid with the above coordinates allow to create an measured data array reflecting the scattering field of the object at the time of observation. The size of the array is being calculated by formula (2), and the resolution and volume of the cubic observation zone is easy to control by changing the \(R\) and \(V\) parameter accordingly. The above formulas allow you to select the volume and resolution of the observation zone needed to solve problems, depending on the dimensions of the observed object. At the same time, each node of the calculated grid is attributed to the module value of the induction vector of the measured scattering field, which is coming from the measuring system. An example of the implementation of a qualitative picture of the field with a black-white scale of the observed field induction is shown in Figure 3.

**Figure 2.** The cube of the settlement grid, embedded into the observation zone of the scattering fields, in this case with a resolution of 3 points on the side of the cube (a). Indexing (numbering) of the observation zone settlement points (b). Cubic settlement grid with a resolution of 7 points on the side (c).

Here the dark dots correspond to the weak field, white — strong one. The scale of induction is proportional to the brightness of the marker and extends from black to white. Visualization of such a black-and-white map provides an opportunity to get a qualitative view of the electric or magnetic field induction into the observation area, which can be very useful in the first stages of the study.
Further processing of the presented results allows to interpolate the values of induction in the nodes of the grid — to arbitrary intermediate points in the space between the nodes. Moreover, interpolation can be carried out on the surface of the conventional plane, arbitrarily located to the determined axes of the coordinate system, which allows to carry out detailed visualization in the chosen directions.

3.2. Calculating the settlement points, which include the estimated pixel
The minimally described geometric plane consists of three dots forming it. This plane is used in computer graphics to represent the mesh. A mesh is a set of points in space and their connections to each other, forming a certain number of surfaces, sometimes with adjacent edges. The mesh belongs to the category of vector graphics, which makes it necessary to rasterize it before putting it on display. Rastering [16] is the process of converting data from a 3D view to a 2D image on a selected surface, consisting of individual pixels. The coordinates of each pixel of the plane are calculated from the coordinates of the nearest fixed grid nodes described above. This pixel will be called as the estimated pixel. The estimated pixel stores information about its color (the value of the induction) and the position in the 3D space of the grid. This information is used to determine the neighboring indexes of offset points between which the pixel was located. A formula is used to calculate a smaller offset index:

\[ RL = \text{FLOOR} \left( \frac{PP + V}{PS} \right), \]  \hspace{1cm} (7)

where: \text{FLOOR} — rounding function down to the nearest whole digit, PP — position on a specific axis of the calculated pixel in space. As a PP, its need to position the pixel on each axle by determining the shift index on that axis, which the estimated pixel is to the right, above or deeper, depending on the axis that is framed. The index obtained in Formula 7 can go beyond the calculated volume. To prevent this let’s limit the value of offset indices to the maximum threshold (cube boundary):

\[ IRL = \text{MIN}(RL, R - 1), \]  \hspace{1cm} (8)

\[ IRH = \text{MIN}(RL + 1, R - 1), \]  \hspace{1cm} (9)

where: \text{MIN} is a function of finding among at least two parameters, RL is a smaller offset index without taking into account of going beyond. Formulas (7–9) determine the indexes of offsets of settlement points horizontally (axis X), vertical axis (Y) and depth (axis) inside or on the surface of which is the estimated pixel situated. This is necessary for the bi-linear interpolation of the estimated pixel value between the surrounding points in the observation zone space.

3.3. Interpolation of a pixel within a grid element
In the next step, its necessary to calculate the position of the pixel relative to the surrounding 8 points of the nearest grid nodes. To do this, let’s first calculate the position of the pixel relative to the coordinates of any of the surrounded points of the nodes. In this technique, the left lower rear settlement point (I1) of 8 volumes is selected for this, as shown in Figure 4. In the figure, the conditional settlement pixel (white sphere) is located in the geometric center of the nodes points and its coordinates are counted (red arrow) from the initial settlement point of the I1 node. To calculate a normalized position, the pixel coordinates are being divided onto the distance between the dots — the step of the grid. Based on the conditional equitability of the calculated pixel from the grid nodes, its
normalized coordinates in this case will be \([0.5, 0.5, 0.5]\) which are calculated by the following formula:

\[
NP = \frac{WP - I1}{PS},
\]  

(10)

where: \(WP\) is a vector, representing the position of the estimated pixel in the global space. The normalized coordinates of the pixel reflect its proximity to the nodes of the settlement grid. The lower the value of the normalized coordinate on the chosen axis of coordinates, corresponds the closer the estimated pixel to the settlement point \(I1\), the more — the closer to the next point on the same axis.

3.4. Converting offset indexes into a settlement point index

To convert normalized pixel offset indexes within the grid element — into the real coordinates of the settlement grid, the following formula is proposed:

\[
I(HI, VI, DI, R) = HI + VI * R + R^2 * DI,
\]  

(11)

where:

- \(HI\) — horizontal shift index,
- \(VI\) — vertical one index,
- \(DI\) — depth shift index.

This formula should be applied as many times as the nodes are surrounded by the pixel in question, namely \(n = 8\), each time substituting the coordinates of the relevant node:

- \(I_1 = I(HL, VL, DL, R); I_2 = I(HL, VH, DL, R); I_3 = I(HH, VH, DL, R); I_4 = I(HH, VL, DL, R); I_5 = I(HL, VL, DH, R); I_6 = I(HL, VH, DH, R); I_7 = I(HH, VL, DH, R); I_8 = I(HH, VH, DH, R);\)

where: \(HL\) and \(HH\) — the smaller and higher value of the index horizontally, \(VL\) and \(VH\) — the smaller and greater value of the vertical shift index, \(DL\) and \(DH\) — the smaller and greater value of the index of shift in depth.

3.5. Bi-linear interpolation between points

With normalized pixel coordinates within the settlement grid element, as shown above, it will interpolate the coordinates [17] between the mesh nodes opposite each other and then between the results. This method of interpolation is called bi-linear. Each pixel is assigned a vector of electric field induction, coming from the measuring system, or the vector of magnetic field induction, depending on the type of measurements on which visualization is carried out at the moment. This implies that the measuring system performs vector measurements of the electromagnetic fields. Each vector is described as the size of a module that is not oriented-dependent, and the direction which set by the orthogonal component ratio of the vector. First, its necessary to interpolate the values of the modules by the values of normalized coordinates, calculated in formula 11. The interpolation formula between the two values is as follows:

\[
LI(F, T, P) = F + (T - F) * P,
\]  

(12)

where: \(F\) — initial value, \(T\) — the final value, \(P\) — relative shift from \(F\) to \(T\). This formula also works with the orthogonal component of vectors by applying it to their individual components:

\[
LIV = (LI(V1X, V2X, P), LI(V1Y, V2Y, P), LI(V1Z, V2Z, P)),
\]  

(13)

where: \(V1X, V1Y,\) and \(V1\) — first vector components, \(V2X, V2Y,\) and \(V2\) — values of the second vector components, \(P\) is a relative shift from the first vector to the second. The length of the vector is calculated by the formula:
\[ L = \sqrt{X^2 + Y^2 + Z^2}, \]  

(14)

where: \( X, Y \) and \( Z \) are components of the measured vector on the \( X, Y \) and \( Z \) axes respectively. Since there are 8 nodes of the settlement grid element, let’s first interpolate along the vertical axis between \( I_1 \) and \( I_2 \), using the normalized coordinate value \( Y \) of the calculated pixel as an interpolation indicator. Then we do the same procedure between \( I_4 \) and \( I_3 \), and the results are also interpolated with each other by the value of normalized coordinates \( X \) of pixel as shown in figure 5 on the left. The result of this operation is a vector of electric or magnetic field induction at the point, located directly on the plane, formed by the calculation points \( I_1, I_2, I_3 \) and \( I_4 \). The same bi-linear interpolation must be done with points \( I_5, I_6, I_7 \) and \( I_8 \). The results of both planes are interpolated among themselves by the value of the normalized coordinates \( Z \) of the pixel, as shown in Figure 5 in the center and right. This calculates the final vector of electrical or magnetic field induction in pixel coordinates. By calculated values it’s possible to set the brightness of the pixel, displayed in the range of black to white on the chosen plane, arbitrary crossing the specified volume of the observation zone, as shown in Figure 6. It can be seen that the brightness of the pixels reflects the measurable modular values of \([11, 12]\), and the adjacent areas are also bi-linearly interpolated to illustrate the transitions. The created software allows to choose the arbitrary position of the control plane, on which the modular images are rendered, such as measurement results, as shown in Figure 6 (b). The image shows that the visualization plane is interpolated between the adjacent planes of the nodes. The high gradience of the background on the visualization plane is due to the small number of mesh nodes at the selected observation area interval. Increasing this number even to \( n = 10 \) allows to get a smoother distribution of the measured and interpolated image of the field, as shown in Figure 6 (c). Here, dark areas have a lower value of the measured vector module, light — large. It is shown, that the arbitrary movement, rotation, and scaling of the visualization plane within the scope of the observation — does not affect the accuracy of the interpolation and the representation of the measurable values, coming from the measuring system.

3.6. Animation in Time

To time animation the visualization either modular and vector measurements, it is possible to periodically replace the array of data coming from the measuring system, which is carried out through the time interval set at the program. Since the research of the EMS is mainly carried out in a stationary mode, the intervals of replacement time of arrays are set in the range of units of seconds, which is intended to study the long-term stability of the observed radiations. However, the software has no theoretical limitations for reducing the observation time interval to a small parts of a second, if necessary.

3.7. Volume visualization of the scattering fields measurements results

For 3D imaging, it is proposed to create a series of different cubic volumes, limited by the visualization planes, described above, which are located symmetrically relative to the geometric center.
of the observation area. Moreover, the cubic volumes have different sizes, in a scale that changes with a constant step from the first volume to the last, for example in the total amount of the \( N = 100 \). Besides, the created cubic volumes have a transparency of 99\%, which allows to observe the measured values through all the planes of the created cubic volumes of visualization, as shown in Figure 7. This mechanism, proposed in this paper, also allows to understand what the distribution of electromagnetic fields inside the observation zone, when the coordinates of the external observation point are being changed.

3.8. Color map
The proposed software allows to display the scale of the magnitude of the measured induction not only by the brightness of the marker, but also by its color. To do this, the color marking of the interpolation result from the formula (14) is proposed, in accordance to the scale, shown in Figure 8.

![Figure 7. Visualization of measurable values in the volume of the observation area.](image)

![Figure 8. Map of matching colors and measurable values.](image)

The higher measured value in a particular pixel corresponds the more red the shade of marker becomes, the lower the bluer. The left part of the color map corresponds to the minimum value of the measured value, the right part — the maximum. The scale boundaries of the measured values are set at the program level in the initial dialogue, together with the volume of the observation zone and the step of the calculation grid. Based on above boundary values it’s offered the following expression to calculate the relative CPX pixel coordinate on the above scale, a color matching map:

\[
CPX = \frac{L - MIV}{MAV - MIV},
\]

(15)

where: \( L \) — the length of the induction vector in the calculated pixel, \( MIV \) — the minimum value among all settlement points, \( MAV \) — the maximum value among all settlement points. Formula 15 allows you to calculate the pixel percentage position on the color map. The following expression is proposed to extract the color directly:

\[
TEX = FLOOR(ABS(MOD(CPX, 1)) \times W),
\]

(16)

where: \( FLOOR \) — rounding function down to the nearest whole digit, \( ABS \) — function extracting absolute value, \( MOD \) — fission function with the remainder of the first argument on the second, \( W \) — the width of the texture in the pixels. This function extracts the color of the pixel from the above color map, which is the result of the color visualization algorithm, shown in Figure 9. In the figure, the small values of the measured values (dark spheres) correspond to colder colors on the chosen visualization plane, strong values (light spheres) — hotter. As in previous cases, the visualization plane may be arbitrarily between the nodes of the settlement grid, which does not affect the correct display of the marker color, according to the chosen scale. A more detailed picture of the modules measured distribution is shown in Figure 11 (b), which is achieved by reducing the step of the settlement grid. The proposed color imaging techniques also can be apply to all animation algorithms, described above — in time, 3D, or interpolation at the arbitrary position of the chosen visualization plane.

![Figure 9. Color visualization of modular measurements.](image)
4. Results

4.1. Description of the resulting product

Thus, the visualization system is part of the system of mapping the electromagnetic radiation of the object, the structural scheme of which is shown in Figure 10. The figure shows the following elements of the mapping system: P — positioner linear, ID — measuring device, INT — interface between the measuring device and software product, PPV — described in this paper software application "Visualization." The positioner is a linear manipulator that is designed to install a measuring sensor at the point of the observation zone, with the coordinates, which set in the grid by initial dialogue with the software visualization product. At the initial stage, the measuring sensor can be moved to the specified distances by some linear guide elements — rakes, oriented along the axes of a given system of coordinates of the object of the study. A measuring device is a vector magnetometer for measuring the magnetic field, or a measuring capacitor to measure the electric field. The interface is based on the PC1716 device [20], which multiples measuring channels, makes analog-digital conversion, and transfers information to the software environment in the language of C.

4.2. Comparative analysis of created imaging techniques

4.2.1. Spot visualization

Figure 11 (a) shows an example of point imaging of an electromagnetic field as the easiest implementation of this procedure. This technique is more productive, but less informative. The researcher does not see the values that appear between the two calculated points. This visualization is more difficult to understand, when it is superimposed on the image of the electronic device under study.

4.2.2. Cubic visualization

More advanced is the cubic imaging of the electromagnetic field shown in Figure 11 (b).

In this case, cubes are used instead of dots, the sides of which are equal to the distance between calculated points. The surface of the cube has transparency, depending on the magnitude of the measured field. With this approach, the researcher sees sharp transitions between the two calculated values, and artifacts may be observed under some viewing angles. At high resolution (number of points) of the calculated volume, the number of frames, processed per second, can be decreased, which in some cases may be critical. Changing the cubes position in space leads to incorrect visualization. This technique is less productive than the point one.

4.2.3. Spherical visualization

This technique, illustrated by Figure 12 (a), is a cubic one extension, but instead of cubes, spheres are supposed to be used here. The sizes of the spheres are several times greater than the distance between the calculated points. This is necessary to ensure that the spheres are being overlapped. The surface of
the spheres also has transparency, depending on the field induction at the point within the sphere. This transparency allows to mix the colors of the spheres, forming more correct values at adjacent transitions, than in the case with cubes. The spherical imaging technique is less productive than the cubic one but lacks some of its drawbacks.

4.2.4. Flat visualization
Unlike previous methods, this technique does not link the geometric shape with each point of measurement. Instead, it is proposed to use a plane, on which the induction of the electromagnetic field is being measured, as shown in Figure 12 (b). A more accurate method, the bi-linear interpolation, is used to find the characteristic of the field between the nodes of the grid. This technique is devoid of artifacts. The number of frames, processed per second, does not depend on the calculated volume resolution. Any geometric 3D shape consisting of planes, can also be easily used in this technique. Besides, the technique supports the visualization of several planes at the same time, which allows to form a visualized volume as 3D visualization.

![Figure 12. Spherical (a) and flat (b) visualization.](image)

4.3. Benefits and prospects
The proposal provides visualization by using the brightness and color of markers. The software product offers the user a choice — visualization on a plane, or in 3D-space. The proposed technique allows to restore dependence by a minimum number of points, which reduces the number of measurements. An applications of the proposed system consist in different approaches to the analysis of the outer fields created by the aircraft. Moreover, the fields under study can be any, not only electromagnetic — temperature, fields of gravity, fluid flow rate, fluid speed and others. One of the promising applications is the mapping of the electromagnetic field in the cockpit of an advanced combat destroyer. Figure 13 shows the cockpit mapping grid used in fighter fire control technologies [24]. The figure shows that the cockpit of the aircraft is divided into cubic elements with a side of several centimeters, which determines the required accuracy of positioning of the measuring device, and the accuracy of visualization respectively.

![Figure 13. Dividing the cockpit work area into discrete cells.](image)

5. Conclusion
This work implements an algorithm of flat and 3D visualization in the space and time of the electromagnetic scattering field induction created by aircraft in the surrounding space of a given volume. The formulas and rules have been obtained to determine both the position of the measurement results and their order of presentation in the general array. The visualization options are considered, the algorithm of bi-linear interpolation is implemented on the example of calculating the vector of
electrical field induction. A method of 3D display of measurable information is proposed. The algorithm of the initial definition of the number and position of points in the volume of the observation zone is realized. A color map is offered — a scale of measured values. It is possible to use a system of mapping scattering fields of power systems during research and development of aerospace technologies. In the next stages, the authors will develop the results in the direction of further automation of measurement processes, expanding the initial dialogue with the software product, and creating a permanent prototype system to demonstrate and improve it. In the next work, the authors plan to describe the results of mathematical and physical simulation of the proposed technology, for which the choice of object and preparation of equipment are carried out.

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