

Thermal Computer Modeling of Laser Gyros at the Design Stage: A Promising Way to Improve Their Quality and Increase the Economic Efficiency of Their Development and Production

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Abstract

In the paper, we consider the ways to improve the quality and economic efficiency of development and production of complex innovative electronic devices, among which are laser gyros (LGs). Development, manufacturing and testing of high-tech LG are relatively expensive. The accurate thermal modeling at the early stages of LG designing is an effective way to reduce overall costs owing to noticeable savings of expenses on multiple-laboratory tests of the LG under development and its re-design due to overheating. Use of the inexpensive Russian computer system ASONIKA for thermal modeling provides yet another boost to cost efficiency. In the paper, details of application of the electro-thermal analogy method, finite difference method, grid method, graph method in ASONIKA are described. The developed algorithm of creation of LG thermal model with the procedure of step-by-step disaggregation (zooming technique) is presented. The process of LG modeling by ASONIKA computer system is explained; the created LG thermal model in graphic view and the obtained thermal field of one of PCB in colored view are demonstrated. Electronic components prone to overheating are specified. The paper also presents the results of empirical verification of modeling with actual measurement of temperature by the thermal sensors installed in places corresponding to the model nodes; those measurements confirmed high accuracy of ASONIKA-based simulation.

1 Introduction

1.1 Why is thermal simulation essential at the early stages of designing?

The quality and the reliability of electronic devices (EDs) are largely determined by the ability to estimate possible overheating of electronic components (ECs) at the development stage and to prevent it during the device actual operation, since operation at excessive temperatures significantly limits the lifetime of components and increases their failure intensity. In fact, the growth of temperature from 20 to 80 °C leads to raising the failure intensity of semiconductor devices in 3–4 times, resistors in 2–3 times, capacitors in 6–8 times, IC in 6–10 times (Udalov 2007). The analysis of ED development features showed that most engineers understand what a significant impact temperature has on the operation of devices. But due to the lack of attention to thermal design, overheating is discovered too late, often resulting in costly error correction (Aldham 2017; Yovanovich 2005). This is because 40% of design engineers consider thermal design “a low priority” when developing their devices. For many of them, the main priorities are meeting the customer requirements for parameters, using innovation and ensuring the reliability of devices. But the temperature level in some cases is a decisive factor limiting ED parameters (Madera 2015). The precision of the laser gyro navigation systems significantly decreases in conditions of the change of the environmental temperature (Li et al. 2013).

One of the key characteristics of ED is the capability to withstand both external thermal loads and internal ones, arising from the self-heat emission. The actual distribution of the thermal field in ED is determined by combination of these two factors. The most critical problem herewith is the local

overheating of ECs placed on PCB, since it may cause changes in the parameters and/or failure of the EC in operating ED. Overheating of up to 10°C is known to reduce EC lifetime by 50% when working at high temperatures.

So, it is exactly the accurate thermal design at the early stages of development that allows achieving all of specifications finally. With automated computer simulation systems engineers no longer need to have an extensive knowledge of thermal design in order to create precise temperature fields of projected ED in actual operation regimes (Aldham 2017; Cook 2017). Generally, computer simulation at the early stages of projects gives the possibility to accelerate the projecting up to 30 % with reduction of design mistakes, thus yielding the real economic profit.

1.2 Thermal computer simulation principles and software

Computer-aided engineering of thermal processes in electronic systems is based on any or all of three ways of the heat energy transfer: conduction, convection, and radiation. All thermal simulation software packages (SPs) use very similar approach grounded on heat transfer physical laws and equations, with many of the packages commercially available (Aldham 2017; Ellison 2011) and applied by researchers (Cheng et al. 2005; Raja et al. 2015; Cook 2017).

We have analyzed popular foreign SPs for computer simulation of thermal processes in our ED – densely packed three-axis LG with electronics – and have encountered problems with application of them. Important problem is adaptation of foreign SPs to the components database and typical designs used in Russia, as well as to Russian design standards. Consequently, high price of foreign SPs and time required for their adaptation will significantly increase cost and time of development. It is noteworthy that foreign literature does not provide any information on simulation of the distribution of thermal fields in three-axis LG with electronics.

That is why the best choice for us was to use the inexpensive Russian computer SP ASONIKA which had proved the true results of thermal modeling in numerous projects for aircraft and cosmic complicated EDs (Shalumov 2013). ASONIKA permits to simulate all types of the heat transfer and imitate the real conditions of ED exploitation. Besides, ASONIKA includes full information on Russian components and materials database, Russian design standards.

1.3 Laser gyro features and main purpose of our study

LGs on ring lasers have been in widespread use since the 1980's and nowadays all airliners and many other vehicles are equipped with them (Klein 2017). LGs for application in navigation systems of aircrafts are to be especially reliable.

Development, manufacturing and testing of high-tech LGs are relatively expensive. This is why only a few companies in the world produce LGs.

Previously, we have introduced cost-effective and technically efficient computer-based modeling methods for creating the unified LGs production management system with automated quality control system

(Belov et al. 2016).

Also we have presented concepts for the application of computer simulation methods in LGs development projects to align their design principles with the task of ensured production of reliable high-quality devices (Kuznetsov et al. 2020; Kuznetsov et al. 2020).

Here we report on our further research on three-axis LG of the type shown in Fig. 1 (Lukyanov et al. 2013).

This LG is constantly being improved in specifications, but new modifications have the same dense specific design with three ring laser sensors and a set of electronic blocks – PCBs compactly placed in free spaces of the common casing-shield. Naturally, the tightness of arrangement causes an increased heat emission in the interior volume. Besides, LG may operate in wide temperature range.

To ensure reliable operation of LG it is necessary to exclude local overheating and noticeable temperature gradients in the thermal fields of the device. The only and efficient way to analyze the thermal behavior of LG at the early stage of device development is thermal modeling. Backed by inexpensive Russian SP ASONIKA for computer-aided simulation of LG thermal behavior this approach reduces total cost of development since it allows to go by without multiple-laboratory tests of the LG under development and its re-design due to overheating.

In this study the task was set to develop an algorithm of LG computer thermal modeling, and to perform the complete modeling.

Problems of LG computer simulation have been touched upon in a number of papers already. The paper (Naveen et al. 2013) on computer modeling of three-axis monoblock LG describes, in fact, the results of mechanical modeling of the ring laser resonator (sensor) of LG without any electronics with the aim to identify its resonance frequencies. In the paper (Abaturov 2019) the results of thermal simulation of single-axis ring laser resonator (sensor) of LG are presented. In our work the object and scope of research differ – it was necessary to perform thermal simulation of three-axis LG, including – in addition to the three ring laser sensors – a complete set of electronic units, which determine the largely reliable operation of the overall device in a wide temperature range.

2 Methods Of Lg Modeling And Algorithm Of Creation Of Lg Thermal Model

2.1 Methods used in three-axis LG modeling with ASONIKA

Modeling process in ASONIKA is based on the electro-thermal analogy method, finite difference method, grid method, graph method, zooming technique.

The method of electro-thermal analogy allows in case of difficulties in determining the required parameters of the investigated process to move to the analysis of another process, which is equivalent to

the investigated one, but free from its disadvantages. Many scientists consider this method to be useful (Man 2011). Electro-thermal analogy is based on formal similarity of mathematical descriptions of heat conductivity and electrical conductivity processes (Kofanov 2017). It is also important that the engineer-developer of electronics, not being a specialist in the field of thermal engineering can more easily imagine thermal processes, using familiar terms similar to those of electrical engineering. To apply the principle of electro-thermal analogy, the topological models were uniformized based on mathematical description of different physical processes, as shown in Table 1.

Table 1 Uniformity of different physical processes, illustrating their exchangeability

Uniformed variables and parameters of physical process models	Electrical model	Thermal model
Model's node variable, φ	Electric potential of the node, φ	Temperature of isothermic part of design, T
Model's branch variable, ψ	Branch current, I	Heat flow between isothermic parts (heat emission power), P
Dissipative branch parameter, α	Electrical conductivity, G_E	Heat conductivity, G_T
Conservative branch parameter (1st kind), β	Electrical capacity, C_E	Heat capacity, C_T
Conservative branch parameter (2nd kind), γ	Electrical inductance, L_E	Thermal inductance, L_T
$\alpha (\varphi_1 - \varphi_2) = \psi$	$G_E (\varphi_1 - \varphi_2) = I$	$G_T (T_1 - T_2) = P$

In thermal modeling LG we use non-directional graphs, which allow us to create a structural topological model of the device in the form of nodes corresponding to parts and units of the device, and show the relationship between them, illustrating the thermal processes occurring in the device.

Uniformed variables and parameters of electric and thermal models are given in the first column of Table 1. The variables describe the input and output data of the model. The former ones are set before or during the simulation and the latter ones are obtained as a result of the simulation. Their relationship is determined by the model structure and the values of the graph branches' parameters. Parameters of branches are often constants, but sometimes they can also depend on dissipative and conservative parameters. The formulas in the bottom line of Table 1 illustrate the uniformity of mathematical equations of different electric and thermal processes and also the equation in a uniformed version.

In ASONIKA, the finite difference method (FDM) is used in thermal modeling, which is also called the grid method. In this method, the continuous task of mathematical physics is replaced by its discrete analogue,

the "difference scheme". In fact, the area of continuous argument changing is replaced by a limited set of points – nodes, the collection of which forms a grid. Such a grid may be considered as a non-directional graph.

In some cases, modeling is based on the finite element method (FEM). But a classic FEM usually requires the grid of a large number of elements, resulting in insufficient computer memory or slow computation (Liu 2020). It is necessary to note an important advantage of FDM as compared to FEM: FDM is characterized by the relative simplicity of the decisive algorithm and its software implementation. For these reasons, we made thermal simulation using FDM as it is arranged in ASONIKA.

Three-axis LG is quite a complex device for thermal simulation, as it consists of a variety of parts and units, which are made of different materials, have different shapes and are packaged in a non-standard manner. So, our decision was to use method of disaggregation (zooming technique) in process of modeling LG. It means that the analysis of the simulated object is performed with a sequential increase in the degree of discretization, i.e. with a growth in the spatial resolution of the whole object and its parts, which provides an improvement in modeling accuracy. Similar way was successfully implemented, for example, in research (Okada et al. 2004), where mesh with finer discretization was superposed at the region to zoom the spatial resolution of analysis. In our research we were able to apply zooming technique because ASONIKA has two subsystems: with ASONIKA-T we could provide macromodeling LG by dividing it on isothermic parts: ring laser sensors, PCBs, casing-shield, supporting frame, internal air gaps, after that made fine modeling of each PCB with ASONIKA-TM to determine the temperature of every EC.

2.2 Algorithm of creation of LG thermal model

To fulfill the task of our study we developed an algorithm of LG computer thermal simulation basing on zooming technique (Fig. 2).

As it is seen from Fig. 2, at the first stage the macromodeling of LG is carried out with the analysis of thermal processes in the parts of LG, including PCB, and then the degree of analysis discretization is increased up to the determination of temperature regimes of each EC.

Modeling on developed algorithm allows both to estimate the actual temperature of EC, as well as to determine whether temperature regime of EC corresponds to permitted level of thermal loading. The high reliability requirements of the ED operation demand that the maximum EC operating temperature be limited even lower than indicated in the specifications. Typically, ratio of actual temperature to maximum allowed operating temperature – so called coefficient of thermal load – must not exceed 0.8.

Critical moments of calculations in algorithm are the estimations of thermal loadings at the steps of modeling so that in case of recognized overheating engineer could find the optimal way for deciding problem (change EC for more stable to thermal influences or change the PCB design to decrease thermal loads). Discovering those shortcomings, he can eliminate weak points in the design early at the development stage, before manufacturing the prototypes and tests.





3 Lg Thermal Model And Experimental Verification Of Simulation

3.1 LG thermal simulation process and results

While modeling LG with ASONIKA we considered all the types of thermal processes available in LG – conduction, convection, and radiation – because ASONIKA software based on the main heat transfer equations that follow from the Fourier law and the Newtonian cooling law describing these processes. In calculations the finite-difference form of equations is used.

Applying the zooming technique, mentioned in 2.1, in the first stage of simulation process, we performed LG macromodeling. Thermal macromodel of LG was developed in the ASONIKA-T subsystem as a model of heat flows displayed as a non-directional graph. Nodes of this graph simulate isothermic parts of LG (listed in 2.1), and its branches show heat flows between these parts corresponding to the type of heat transfer process, as designated in Table 2.

Table 2 Designations of branches corresponding to different types of heat transfer

Branch designation	Explanation
	Conduction
	Radiation
	Contact heat transfer
	Natural convection

The ASONIKA-T subsystem automatically generates models of typical structures, and for non-typical structures there is a graphic interface enabling the engineer-designer builds a topological model himself. When modeling LG we used both options, because part of the LG design elements has a typical form and part – atypical. In the process of modeling we got information about thermal parameters of the LG structural materials (heat conductivity, heat capacity) from databases of ASONIKA-T subsystem and specifications. ECs specifications have been stored in databases of ASONIKA-T, and we used these data also while modeling.

For explanation of the modeling process a sketch of zone of LG internal volume is shown and a model of this zone as non-directional graph is presented in Fig. 3 (parts and nodes numbering corresponds to their positions in the complete model).

The total model of three-axis LG with electronics is presented in Fig. 4. In the lower left corner of the Fig. 4 the heat emission power sources are shown corresponding to ring laser sensors and each PCB, which are designated as a current source according to the electro-thermal analogy (Table 1).

The model is presented as a set of fragments, which automatically combined by ASONIKA software joining nodes with the same numbers.

Input data were the given environmental temperature, the heat emission powers of ring laser sensors and each PCB (as a sum of heat emission powers of all ECs mounted on the PCB). Output data were the temperatures of all parts of design, all ring laser sensors and all PCBs.

Based on the calculation results, the data were displayed as a table of temperatures in the nodes of the LG model.

In the second stage of modeling in accordance with the zooming technique, we moved on to modeling each PCB separately in order to determine the temperatures of all ECs mounted on it. Here we used the ASONIKA-TM subsystem, which automatically builds (basing on FDM) a grid for every PCB as a non-directional graph.

Further we present in Fig. 5 the results of modeling of one of the PCB – digital electronic block, as the colored image of its thermal field. It is a good choice to illustrate the simulation results because of the large number of ECs mounted on it: about 350 ICs, transistors, diodes, resistors, capacitors are placed on both sides of the PCB.

It should be noted that the sharp boundaries between EC and the surrounding zone are explained by built-in capacity of the ASONIKA-TM subsystem to determine and display the average temperature of each separate EC.

Among all the ECs of this PCB, an excess was found in 5 resistors (coefficients of thermal load in the range 0.85–0.88), which is 1.4 % of the total number of ECs.

At the same time, it should be noted that at the given environmental temperature of + 60°C a number of the ECs of this PCB (about 10%) operate at elevated temperatures (up to + 100°C), which, as it is known, leads to increased of EC failure intensity.

We emphasize that ICs are even more heat-sensitive – temperature rise from 20 to 80°C in them can increase their failure intensity by an order of magnitude, as mentioned in Sect. 1. An important EC of the digital electronic block – Programmable Logic IC (PLIC) appeared excessively heat loaded: at the given environmental temperature + 60 ° C, the temperature of the PLIC on the results of the simulation is about + 76°C, and on the results of the laboratory experiment (Sect. 3.2) even higher, namely + 79°C, which should draw special attention.

Thus, at further development of new modification of three-axis LG with increased time of continuous operation engineers should take measures to reduce thermal loads on overloaded ECs.

3.2 Experimental verification of LG simulation

In order to determine the accuracy of LG modeling, a number of experiments were carried out, in which a set of thermal sensors was installed in the device. Thermal sensors with sensitivity 0,5°C were placed at 15 points corresponding to the nodes of the graph in the thermal model. It was found that the thermal model error makes an average 3.4%. Thus, the validity of the three-axis LG thermal simulation with ASONIKA was confirmed and the correctness of our choice of simulation methods and developed algorithm was proved.

4 Discussion

1. The method and algorithm of three-axis LG thermal model creation with zooming technique was developed, which provide LG computer simulation in two stages: 1st stage – LG macromodeling with ASONIKA-T subsystem, 2nd stage – modeling of each PCB with ASONIKA-TM subsystem. These subsystems of thermal simulation ASONIKA-T for 3D devices and ASONIKA-TM for PCBs use equations of the classical theory for all types of heat transfer, interpreted in the finite difference form for computer calculations. So, we were able to consider all types of thermal processes occurring in LG.
2. The computer modeling of LG was carried out using the proposed method. Thus, at the 1st stage of modeling average temperatures of LG parts and PCBs were determined, at the 2nd stage – temperatures of each EC.
3. The compliance of the calculated coefficients of thermal load of every EC with the given maximum permissible value of 0.8 was estimated. It was found out that at the environmental temperature at + 60°C there are a number of overheated ECs on the PCBs with coefficients of thermal load over 0.8. It was also identified that some ECs operate at elevated temperatures (up to + 100 ° C), which is known to increase the failure intensity. Thus, at further development of new modification of three-axis LG with increased time of continuous operation engineers should take measures to reduce thermal loads on overheated ECs.
4. In the study the functionality of the method and algorithm in the process of designing a real LG was tested and the accuracy of modeling was verified experimentally with temperature sensors placed in 15 points of the device, corresponding to the nodes of the graph. When comparing the results of temperature measurements with the results of thermal modeling, it was found that the thermal model error makes an average of 3.4%.

5 Conclusion

The results of the research confirmed that the thermal modeling with ASONIKA creates an opportunity to control the thermal loads during the LG development, simulating different regimes of exploitation. Thus, using simulation, it will be possible to reduce the cost of numerous tests and re-design of the device, so that the economic efficiency of LG development and production will increase. Additional benefit in cost

may be provided by the use of Russian system ASONIKA instead of expensive foreign computer simulation programs that require adaptation to domestic element base and standards.

The developed method has a good versatility and can be applied to virtual computer modeling with ASONIKA when designing complex cyber-physical devices.

Further research will be directed on improvement of the proposed modeling method, and also on definition of economic indicators of efficiency gain of projects on new devices development with applying the automated simulation systems.

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Figures

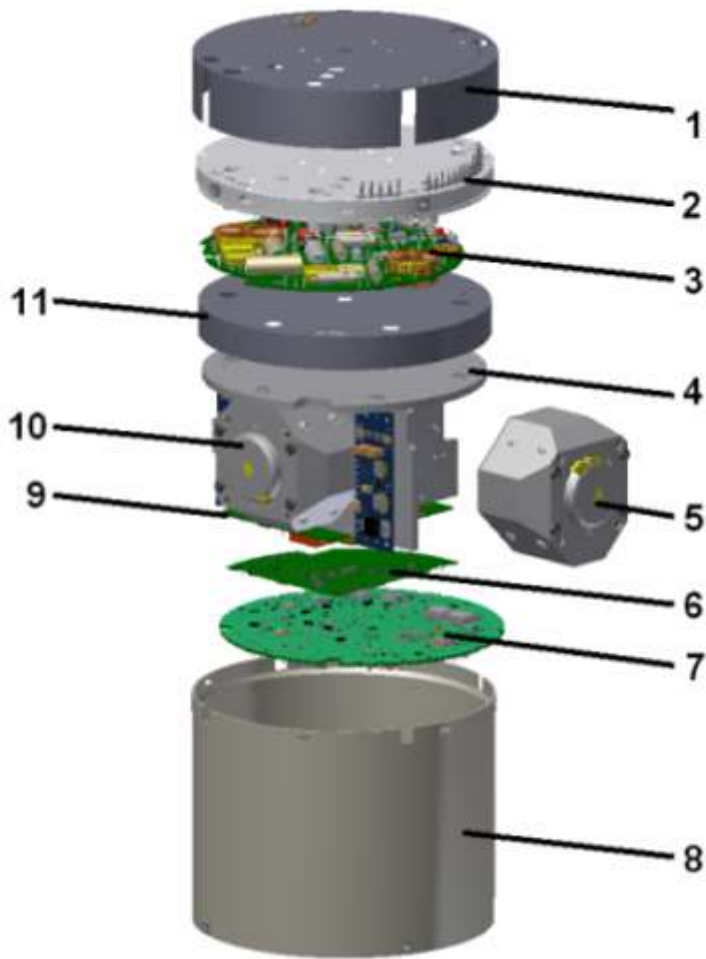


Figure 1

Design of three-axis laser gyros with electronics: 1 – cover of external casing-shield; 2 – disk with pin contacts; 3, 6, 7, 9 – PCBs; 4 – supporting frame; 5, 10 – ring laser sensors; 8 – external casing-shield; 11 – internal shield

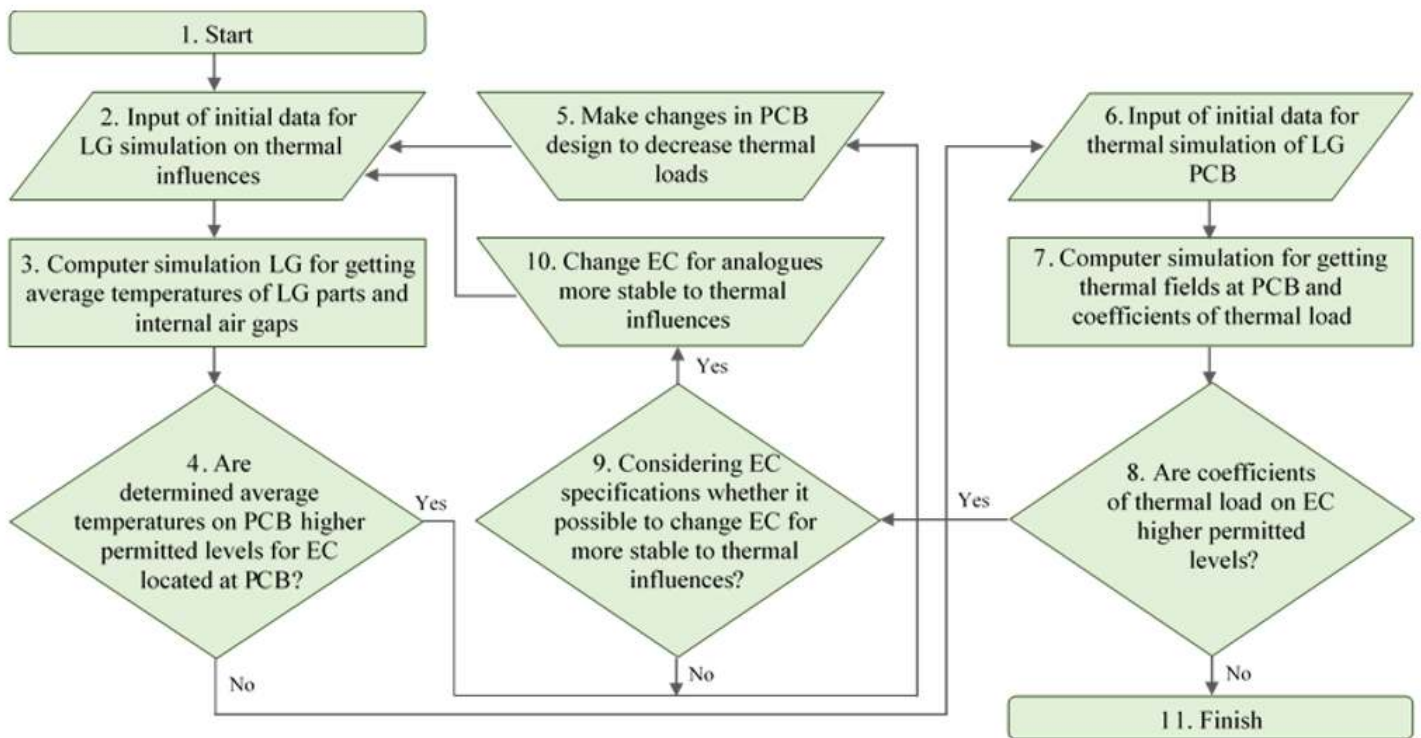


Figure 2

Algorithm of laser gyro computer thermal simulation

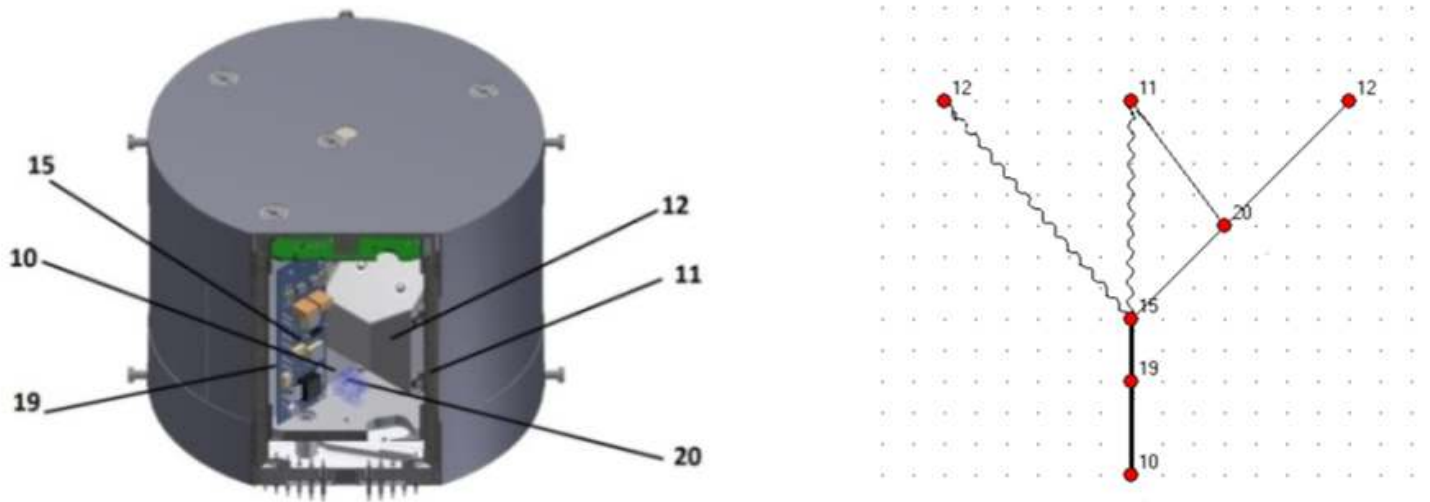


Figure 3

Zone of laser gyro internal volume and its thermal model: 10 – frame, 11 – case, 12 – Z-axis ring laser sensor, 15 – PCB, 19 – PCB radiator, 20 – air gap

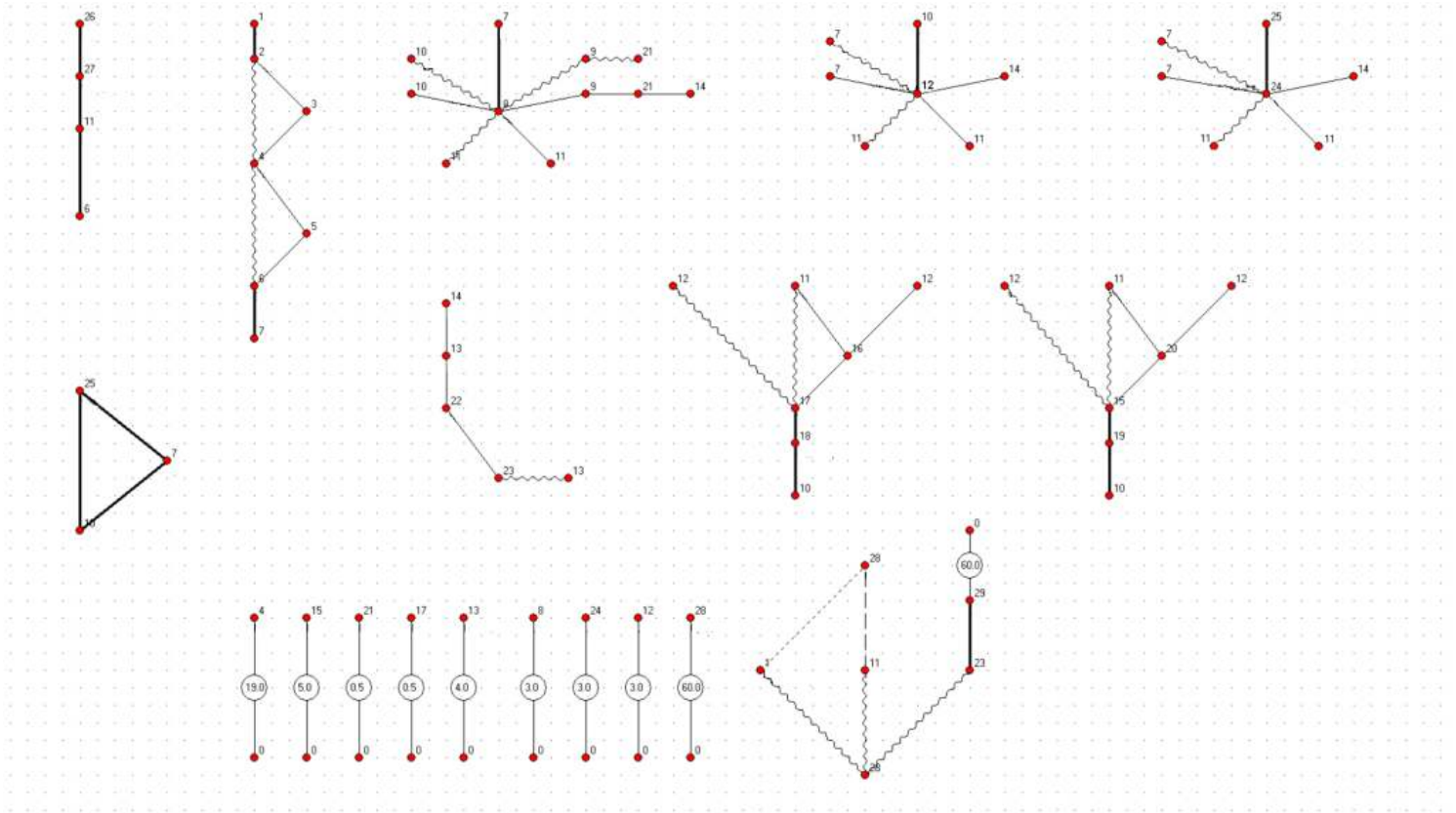


Figure 4

The total thermal model of three-axis laser gyro with electronics created with ASONIKA (figures correspond to nodes numbering to be designated by the engineer-designer in the process of simulation)

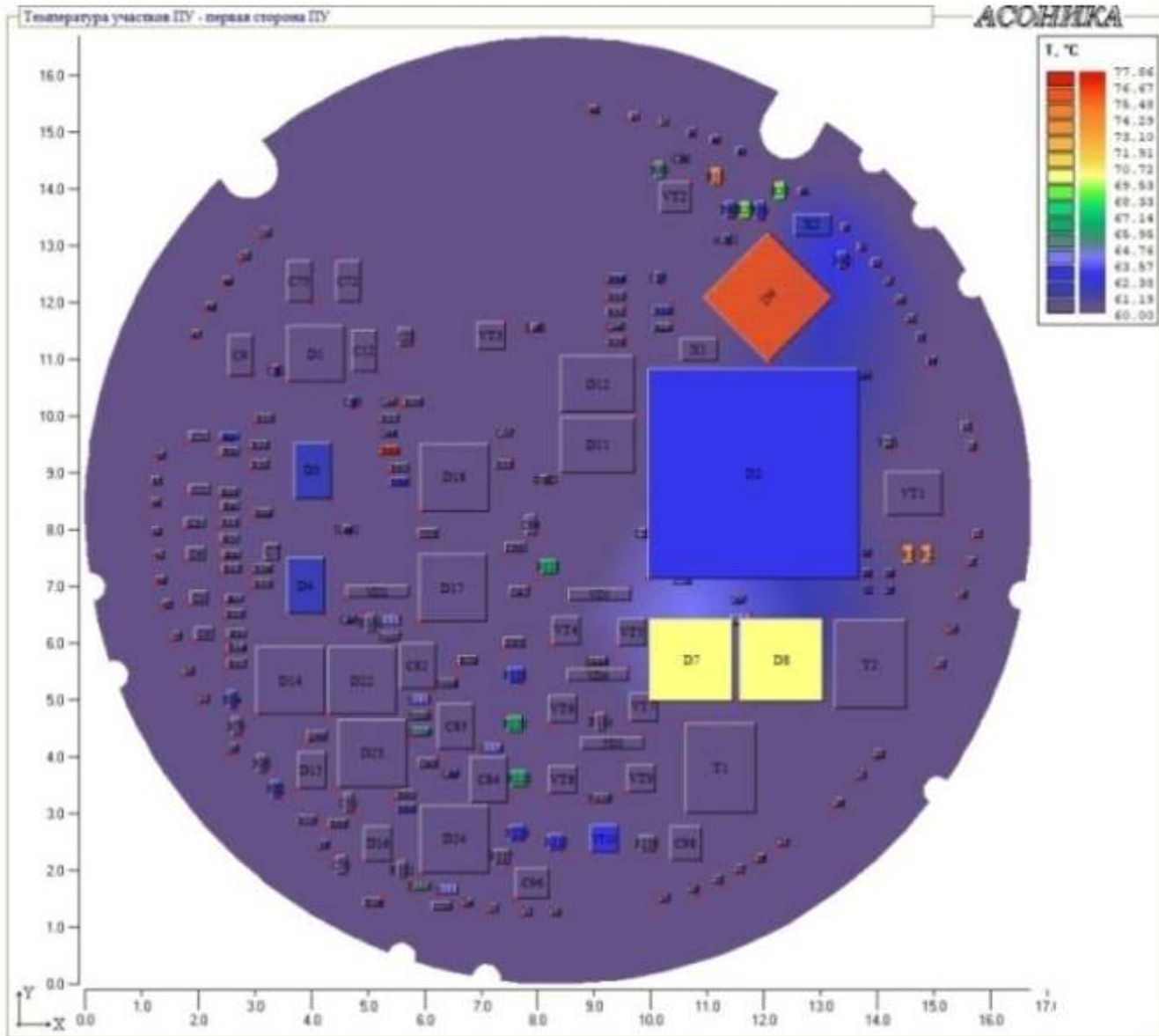


Figure 5

Thermal field of the PCB of laser gyro in the subsystem ASONIKA-TM after modeling the thermal processes with indication of temperature of each EC