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ESTIMA: A thermal simulation software for the optimal design of printed circuit board in the automotive industry

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Abstract

The optimisation of the design of printed circuits boards (PCB) for automotive junction boxes is leading the industry towards the inclusion of the numerical prediction of local temperatures at the board and the electrical/electronic components in the initial stages of the design process. The paper shows the modelling and numerical characteristics of ESTIMA, an integrated software specifically developed for the numerical prediction of the coupled electrical and thermal fields in a PCB with active electrical or electronic components. The software includes the modelling of the conduction heat transfer through an heterogeneous solid (board and tracks) with temperature dependent physical properties, the modelling of the electrical field, submitted to local differences in resistivities and also to heterogeneities (tracks, solders and jumpers), and the thermal modelling of electrical (fuses, relays,) and electronic (solid state relays) components. The program is based on a second order accurate finite volume formulation. The thermal field is computed in a regular 3D grid, fine enough to resolve the track shape, while the electrical field is computed in a finer 2D mesh that solves the details of the electrical intensity field within every active track. Components are modelled as a finite set of nodes, taking into account their intrinsic power dissipation, their connection to different points of the board and their relation to the ambient both through convection and though radiation processes. Extensive comparison with experiments has allowed Lear Co. to use this software as a standard tool in the design process of PCB's.

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1 Introduction

Heat removal from electronic circuit devices has become progressively important, following the continuous process of miniaturisation of electronic instruments. A significant amount of the effort of the heat transfer research community is being directed to this end. The work of Incropera [1] still constitutes an excellent review of convection options available for cooling electronic equipment, from single phase natural, forced or mixed convection to pool and forced convection boiling and two-phase thermosyphons. A great fraction of recent work deals with the study of heat transfer characteristics of 2D or 3D arrays of regular heated blocks (Asako & Faghri [2]; Fushinobu et al. [3]; Jubran et al. [4]; and many others...). In all cases the study addresses the problem of cooling printed circuit boards (PCB) with surface mounted heated blocks, which is a problem present mainly in the computer industry.

In the automotive industry the problem of heat removal from PCB's is becoming of progressive importance for reasons similar to those faced by the computer industry. New generation of automobiles incorporates more and more commodities and functions that are governed and controlled through a progressively smaller junction box, where high power PCB's coexist with electronic boards. Moreover, the space made available within the automobile to hold this box is also becoming smaller and under poorer heat exchanging conditions, reaching the "insane" ambient of about 100°C, near the engine.

Under these perspectives, the design of PCB's for automotive junction boxes is becoming more and more dependent on an optimal heat transfer design, with the same kind of fundamentals problems faced by the computer industry and with a very important additional one: the automobile industry deals with high intensity currents, of the order of 10 to 100 A, that give rise to an important amount of heat generated not in components but directly on the tracks. In this case, the interaction of active components and substrate, of convection/radiation and conduction, is of great importance. There is also a lot of work done on conjugate heat transfer (convection + conduction) for discrete heat sources, or for radiating heat transfer in enclosures, or for just single phase natural or forced convection from heated blocks mounted on surfaces, still addressed to the computer industry problems (Heindel et al. [5]; Wu and Cengel [6]; etc.

Commercially available heat transfer software lacks of integration capability of the intrinsically coupled electrical and thermal problem, with the added effect of connected electrical or electronic components. This paper shows the modelling and numerical characteristics of ESTIMA, an integrated software specifically developed for the numerical prediction of the coupled electrical and thermal fields in a PCB with active electrical or electronic components. The software includes the modelling of the conduction heat transfer through an heterogeneous solid (board and tracks) with temperature dependent physical properties, the modelling of the electrical field, submitted to local differences in resistivities and also to heterogeneities (tracks, solders and jumpers), and the thermal modelling of electrical (fuses, relays,) and electronic (solid state relays) components. ESTIMA can simulate single or double-sided PCB's with pins or variable length jumpers.

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2 Governing equations

2.1 Thermal field

The microscopic energy conservation equation can be written as

$$\rho C_p \frac{\partial T}{\partial t} + \{G+S\} = \frac{\partial q''_x}{\partial x} + \frac{\partial q''_y}{\partial y} + \frac{\partial q''_z}{\partial z} \tag{1}$$

where ρ and C_p are the density and heat capacity of the solid, respectively, q''_x, q''_y and q''_z denote the heat flux components in the x, y and z directions, respectively, G is the heat generation by Joule effect per unit volume, and S stands for the heat exchange rate with the surroundings, also normalised per unit volume. The *S* term may include contributions from surface heat radiation and convection as well as external heat inputs from the electronic components. Assuming that Fourier's law for heat conduction applies, Eq. (1) may be rewritten as:

$$\rho C_p \frac{\partial T}{\partial t} + \{G+S\} = \frac{\partial\left\{k_x \frac{\partial T}{\partial x}\right\}}{\partial x} + \frac{\partial\left\{k_y \frac{\partial T}{\partial y}\right\}}{\partial y} + \frac{\partial\left\{k_z \frac{\partial T}{\partial z}\right\}}{\partial z} \tag{2}$$

2.2 Electric field

The electric field is calculated in the x-y plane for each side of the board with electrically active metal tracks. The microscopic conservation equation for the electric charge, applied to a volume unit within the metal track, may be written as

$$\nabla \vec{i} + s = 0 \tag{3}$$

In Eq. (3) the vector *i* is the electric intensity flux and *s* denotes the intensity source term per unit volume. This term is used to characterise the effect of input and output electric currents. The electric intensity flux is related to the electric potential field, V, according to

$$i = \frac{1}{\rho_E} \vec{\nabla} V \tag{4}$$

where ρ_E is the electric resistivity of the metal. Equations (3) and (4) can be combined to obtain the following microscopic conservation equation:

$$\nabla\left(\frac{1}{\rho_E} \vec{\nabla} V\right) + s = 0 \tag{5}$$

A particular form of the above equation suitable for the present case with Cartesian co-ordinates x, y is:

$$\frac{\partial}{\partial x}\left(\frac{1}{\rho}\frac{\partial V}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\rho}\frac{\partial V}{\partial y}\right) + s = 0 \tag{6}$$

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In the calculation sequence, a discrete version of Eq. (6) is first solved for each metal track and then Eq. (4), also in discrete form, is used to compute the electric intensity flux and the corresponding heat generated by Joule effect.

2.3 Components

ESTIMA has the capability of simulating the thermal and electric behaviour of many components as fuses, relays, fet's, etc. The operation of such components, either plugged-in or solded, is governed by the balance between heat generation (by Joule effect) and heat loses to the environment (by convection and radiation) and to the electrical tracks (by conduction). Several studies can be found in the literature related to the numerical simulation and modelling of the components, Vermij et al. [7] presented a simplified model for miniature fuses were heat transfer to the surroundings of the fuse element is neglected. Sasu [8] solved mathematically the partial differential equation which corresponds to the general heating equation of the fusible element. Another studiy [9] made an attempt to solve the realistic thermal field by means of finite elements. Tough this last method seem to be most adequate, they require however, large computer resources. Consequently we have developed a simplified model which offers accurate enough predictions for the coupling between tracks and components. The basic model is constructed by means of different nodes where heat rate is conserved. The attached figure shows the nodes scheme for a typical fuse. The calculation nodes are: T_h (housing), T_e (element), T_{bl} (left blade), T_{br} (right blade), which are close related to the data nodes which have temperatures previously known: T_a (ambient temperature), T_{tl} (track left), T_{tr} (track right). Following this scheme and applying heat conservation in steady state regime, one obtain the expression for the element node:

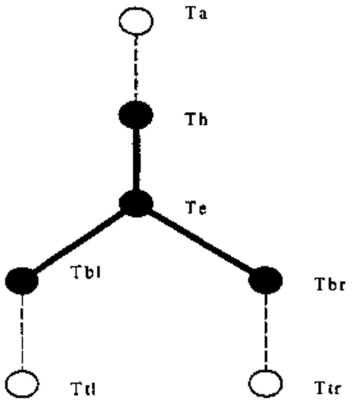

Figure 1. Grid nodes of a fuse

$$-r_{b-c}\,(T_e-T_{bl})-r_{b-c}\,(T_e-T_{br})-\varepsilon\,\sigma\,A\,(T_e^4-T_h^4)-h\,A\,(T_e-T_h)+q_e=0 \tag{7}$$

where r_{b-c} is the inverse of the thermal resistance by conduction, ε the emissivity, σ the Stefan-Boltzmann constant, A the surface of the element, h the convective heat transfer coefficient and q_e the power dissipation by Joule effect. The first two terms correspond to heat transfer by conduction between the element and blades. The third term is the heat transfer by radiation between the element and housing, and the fourth term accounts for the convective heat transfer between the element and the fuse housing. Making the same procedure one obtain similar expressions for the rest of the nodes where the temperatures are unknown.

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The methodology, which was developed, gives for each component the same number of equations and unknowns. The resulting algebraic system of equations, which is non-linear, is solved by means of a multivariable Newton-Raphson method, obtaining as a result all the unknown temperatures, and also, the heat fluxes needed to solve the coupling between electrical tracks and all the attached components.

3 Numerical set-up

3.1 Discretization of the conservation partial differential equations

Equations (2) and (6) are cast into discrete form by means of a second-order accurate finite-volume/finite-difference approach. The electric field is computed on a uniform 2D mesh in the x-y plane. The thermal field is computed in a 3D mesh that is also uniform in the x and y directions but is non-uniform in the z direction, e.g., the direction normal to the board surface. In the top and/or bottom calculation x-y planes the thermal and the electric grid overlap. The grid spacing employed for the electric grid must be considerably smaller than the one prescribed for the thermal grid in order to properly capture the shape of the metal tracks. The user prescribes a unique value of the grid spacing that will be employed both in the x and y directions of the thermal grid. The electric calculation grid is then defined by setting a certain ratio, N_E, of electric grid nodes per each thermal grid node. In the z direction, the user prescribes the thickness of the board and of the metal layers and the number of thermal grid nodes to be employed. A typical thermal grid in the z direction consists, for 1-mm thick boards, of a minimum of 8 non-equally spaced nodes. It is recommended, but not compulsory, to use an average z-spacing of about 0.1 mm. The optimal grid spacing in the x-y plane depends on the particular characteristics of each board investigated. Typically, values of the x-y spacing ranges between 0.10 and 1.5 mm. Typical values for the electric/thermal node ratio are in the range $4 \leq N_E \leq 16$. The heat generated by Joule effect within a single volume cell of the thermal grid is computed as the sum of contributions from the smaller electric volume-cells. The discrete 3D energy conservation equations for each control volume, together with the boundary conditions discussed below, are solved iteratively by means of the conjugate gradient method.

A special treatment is needed for the evaluation of the heat conduction fluxes at the boundaries of each control volume. Each control volume in the 3D-calculation grid corresponds to a unique type of material, but adjacent control volumes may correspond to different solid materials. The special interfaces considered in ESTIMA are the substrate-track interface, the substrate-pin interface and the substrate-hole interface. In evaluating the heat flux at the interface between material I and material II, the best approach consists of using a harmonic average for the interface thermal conductivity. One exception to the use of the harmonic average is the case where two contiguous metal control volumes belong to different tracks. In this particular situation the thermal conductivity at the lateral interface between tracks is set to zero, that is, lateral

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heat conduction between tracks is not allowed. Note that this does not mean that one track has no effect, from the thermal calculation standpoint, on its neighbours. Such a neighbourhood effect, or thermal interaction between tracks, basically due to heat conduction through the substrate, is known to be a factor in the performance of PCB's and is well captured by ESTIMA.

The discrete version of Eq. (6) is iteratively solved for each electrically active track by means of the conjugate gradient method (CGM). The electric field throughout the whole PCB is solved, at each iteration or time step, prior to the iteration of the thermal field. In most practical problems, calculation of the electric field involves an iterative process on its own. The heat generated in electrically active elements that stem out of the top and/or bottom x-y planes, such as pins and bridges, is calculated separately and added to the corresponding thermal calculation cells.

3.2 Boundary conditions

Additional terms are included in the discrete version of Eq. (2) when it is applied to a control volume corresponding to either the top or bottom x-y calculation layer. The term *S* in Eq. (2) encompasses contributions from the heat exchange between the PCB and the surroundings as well as heat contributions due to electronic components and/or to the input/output currents. The first class of contributions includes, in turn, radiation exchange between the surface and the surroundings,

$$q''_{rad} = \varepsilon\sigma\left(T^4 - T_\infty^4\right) \tag{8}$$

as well as convection heat transfer due to the natural convection induced in air,

$$q''_{conv} = h\left(T - T_\infty\right) \tag{9}$$

In Eq. (8), ε denotes the average emissivity of the metal or substrate surface, T_∞ is the absolute temperature of the surrounding air and σ is the Stefan-Boltzmann constant. The accuracy of the convection heat flux evaluated according to Eq. (9) depends upon the validity of the empirical correlation employed to estimate the heat transfer coefficient, h. In horizontal-board calculations, the correlation provided by Sparrow and Carlson [10] has been chosen because of the concordance between the narrow shape of the metal strip used by these authors and the typically shapes of metal tracks in PCB's. The calculation of the convection heat transfer coefficients is individualised for each track because the empirical correlation involves a particular length scale that depends on the track shape. For the bottom surface, heat transfer coefficients evaluated by the empirical correlation are divided by a factor of 2, following the suggestion of McAdams [11]. In vertical board calculations, the well-known empirical correlation of Churchill and Chu [12] is used instead.

4 User Interface and Results

ESTIMA has a specific user-friendly interface that allows the user to perform the operations involved in the definition of the board and in the computation of the

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resulting thermal and electric fields in an easy and intuitive way. A "naturally" ordered Menu, flowing from left to right, guides the user from the initial definition of the geometry of the board towards the final graphical presentation of the resulting fields.

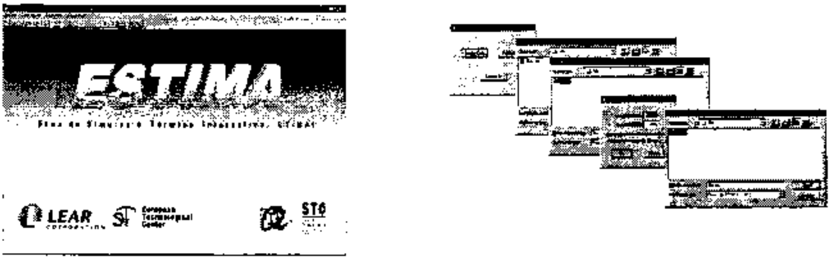

Figure 2. Main screen of ESTIMA and a cascade of –submenus

4.1 Board definition

When the user selects to create a new case the program asks for the file of track definition, which is a standard DXF file generated by a CAD program, for both sides of the board if it is a double-sided or for the solder side if it is a single-sided board. After reading the track definition, the program analyses the tracks layout and looks for errors in files (overlapping, short-circuits, etc.), and also identifies nested tracks if any. Next, the program asks the user for the file containing the drill description, which is the standard DRL file used in design, and contains the position and diameter of all drills present in the board, additionally an offset may be present to adjust the drill position over the board. The program automatically analyses the drills found and decides which ones will be considered as short pins (those connecting tracks in both sides) and which ones will be able to connect a component or an input/output current (those only connected to one track in a side). The holes not connected to any track in both sides will be considered as holes used for board positioning. Finally, if the board is single-sided, the user is asked to indicate the file containing the jumper description if any, the program tests for the coherency between jumper definition and hole position and checks for jumper crossing and overlapping. More than one file can be selected if jumpers of different length are present in the board.
When board definition is completed, ESTIMA analyses the whole board and determines the different families of tracks that are connected by drills and that must be electrically compensated during all simulations and draws it in a new window. Furthermore, the user can edit the board definition by placing or erasing drills connecting tracks and jumpers of any length. The user can also specify the board and track thickness, board emissivity and heat conductivity.

4.2 Definition of intensities and components

User can select any drill that is connected to one track and define the corresponding intensity current. A dialog box appears when user makes a click on the board showing the physical characteristics of nearest drill and its actual

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current intensity. The dialog also informs about what intensity would compensate the track family that contains the selected drill. If user specify an intensity that does not balance the input/output current in the track family all family is displayed in red showing that this problem occurs. Additionally, user can specify the amount of heat added or eliminated through this drill, simulating in this way the heat dissipated by the wire connected.

Components can be inserted by drag and drop it over the board and ESTIMA selects the nearest set of drills and tests if they fit the corresponding layout of component legs. When inserted, a dialog box informs the user about the position and characteristics of component/drills and the current intensity. User can modify the intensity in the corresponding drills for each leg and if current through legs is not balanced, ESTIMA colours them in red.

FETs need an special treatment, as they are mounted by welding its legs directly over the tracks instead of using drills. In this case, the user places the FET on the board and later can adjust the leg position to connect the corresponding track. Finally, the current intensity is entered for each leg and a test of current balance is performed.

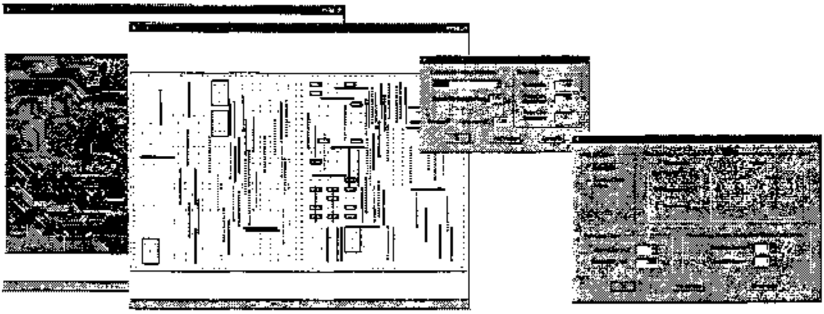

Figure 3 Sub-menus defining the distribution of components and intensities.

4.3 Computation and visualisation of results

After the board is totally defined the calculation can be done by selecting the corresponding menu item. In that case, some of calculation parameters as grid definition and accuracy of calculation can be modified and a final intensity test is performed before launch the calculation part of ESTIMA.

ESTIMA can display 2D maps of temperature and voltage of each side in the board using a configurable colour code. Panning and zooming of these maps can

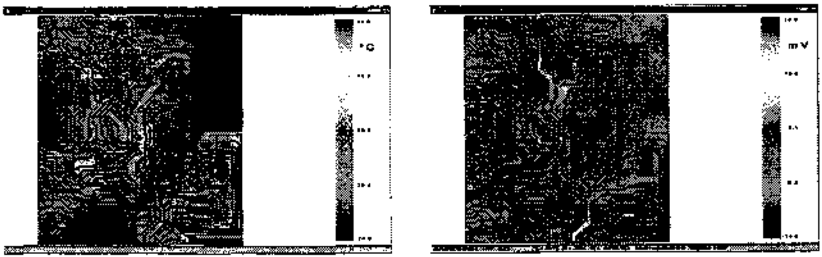

Figure 4. Visualisation of thermal (left) and voltage (right) fields

be done in order to get a better view of the temperature and voltage distribution. In addition to these maps, when user moves the mouse over, the numeric values of all variables are displayed in the status bar of window including temperature and voltage in the point indicated by mouse and, if that point is over a track, the power dissipated by that track is also shown.

In order to facilitate the point identification when maps are displayed the tracks profile of components or solder side can be redrawn over the map shown.

In addition to this visual information, the user gets a set of ASCII files giving detailed and quantitative information about the power dissipated on each active track and component.

4.4 Validation of ESTIMA

A comprehensive set of experiments was planned in order to evaluate the predictive capability of ESTIMA. These experiments were carried out by the Lear R&D department and included a subset of "neat" boards, where components were completely absent, and different subsets of boards with selected components, used to calibrate their thermal node-model.

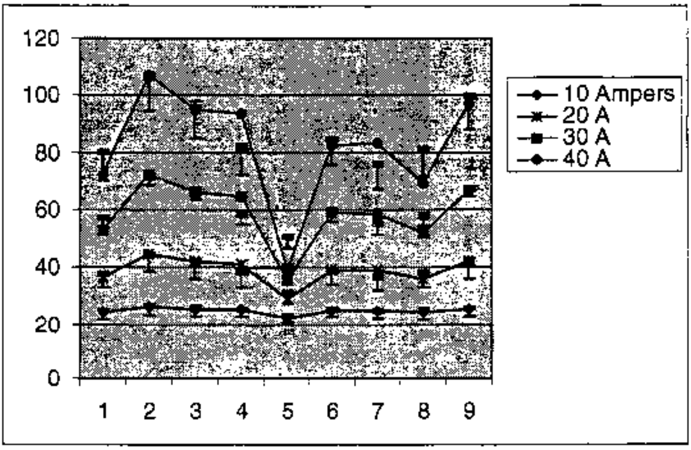

Figure 5. Plot of Temperature vs. position. Solid lines correspond to predictions, bars represent the range of experimental values.

Figure 5 shows an example of the agreement obtained between experiments and predictions in a "neat" board, for a broad range of operating intensities. In this case, the board had active tracks in both sides but no components were present. Nine different points distributed along the two sides of the board were selected to measure both temperature and voltage. Increments of temperature were found to be as high as 90 °C, and, for the maximum intensity, maximum spatial temperature differences were of the order of 70 °C. ESTIMA predictions captured all features and tendencies and quantitative values shown fairly good agreement with experiments even for extreme operating conditions.

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5 Final Remarks

ESTIMA has shown to be a powerful and reliable tool; its computational core incorporates all the essential physics of the coupled thermal-electrical problem of a single or double-sided printed circuit board with active electrical and/or electronic components. Moreover, its user-friendly design has allowed Lear Co. the incorporation of this advanced design tool in the standard design process.

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