A Model Based Enterprise Approach in Electronics Manufacturing

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ABSTRACT

Electromagnetic compatibility and overheating are two key issues in printed circuit board (PCB) manufacturing. Due to design and manufacturing limitations, the Department of Defense (DoD) suppliers put tremendous efforts on testing physical prototypes of PCBs. In this work, we developed a model-based interactive and 3D environment, the predictive environment for visualization of electromechanical virtual validation (PREVIEW), to test and analyze the virtual performance of PCBs, which aids designers assessing manufacturability of PCBs virtually prior to developing a physical prototype. Firstly, a thermal simulation module is developed and integrated into PREVIEW to analyze thermal performance of PCBs. Secondly; electromagnetic compatibility is visualized through simulation of 3D electromagnetic field and noise emission.

Keywords: electronics manufacturing, printed circuit boards, model based enterprise.
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1 INTRODUCTION

Electronic manufacturing is a term used for design, test, manufacture, distribute, and provide electronic components in order to create a circuit card with a particular function (for example an amplifier, radio receiver, or oscillator). Printed circuit boards (PCBs) are electronic manufacturing circuits created by mounting electronic components on a non-conductive board and connecting conductive bridges between them. In this matter, designers of electronics must be aware of various points of failure and how to deal with these problems. Unlike mechanical parts, electrical components are generally unusable through long or heavy use [3]. Discrete analog component parameters tend to drift over time and can cause problems with sensitive designs.

PCBs need to be designed in a way that they resist mechanical shock, vibration, humidity and other environmental stresses [4]. Since solder connections have poor fatigue properties, heavy components should be given extra support rather than simply relying on solder connections. Furthermore, cables need to be carefully supported and strapped down to avoid wear due to moving parts. Connector failure is often a common cause for electrical system failure and attention should be paid to their placement and mounting. Mechanical failures, excessive heat (overheating), and electro-migration (when metal atoms wander into the dividing layers on a microprocessor) are common problems in electronics and affect PCB durability significantly [5]. Furthermore, environmental effects, corrosion, vibration and temperature are of extreme concern. Transient stresses such as electrostatic discharge and lightning can also cause failures. Modern electronic components are prone to damage from high current due to their delicate nature and inability to sink heat [5]. In this matter, fans to improve airflow through enclosure, liquid cooling for high power devices giving off large amounts of heat and careful design are common methods to provide protection against such failures.

Electromechanical assemblies must be designed with the proper temperature, performance, reliability, testability, and environmental characteristics to operate correctly when used in a specific application. To achieve the desired performance and reliability, PCBs need to be tested under extreme conditions of operating stresses, including shock/vibration, temperature, temperature cycling, humidity, contamination, mechanical stress, electrical stress, radiation, electromagnetic, sand and dust, acceleration, altitude, fungus, contamination, and magnetic fields [4]. To increase the performance and reliability and satisfy the customer needs, tests (e.g. thermal shock test, vibration environment test, and test to destruction) can be done virtually using simulation environment and bring out the corresponding data such as mean time between failures (MTBF). The use of appropriate data can ensure adequate part life in a specific application, as well as the reliability of such part [11].

In traditional design methodology, engineering test sequence can be programmed following the design process, and electromechanical test has hardly any influence over improving the circuit design. Testability then is only an afterthought, which means; higher cycle cost, and consequently increased time-to-customer. Shorter development or certification time, reduction of physical prototypes and ability to test situations develop a solid need for virtual design and testing mechanism as the virtual model is always an approximation of reality. The cost of testing (i.e. tools, time etc.) is one of the major concerns in manufacturing. Thus test programs and simulation tools are developed allowing early customer delivery and lower testing cost. Eliminating errors at the beginning of the product development lifecycle significantly reduces any extra cost and diminishes late discovery of error or defect later in the lifecycle (i.e. manufacturing products in a virtual environment to predict and solve problems before they occur on the floor), as shown in Fig. 1. Simply stated, it is critical to get the customer needs right, if not, it then becomes purely chance on whether the developed product will satisfy the needs. In other words, getting customersî needs wrong will result in failure. In this concept, model based manufacturing completes the collaborative design environment between operations, engineering, and supply chain [9].

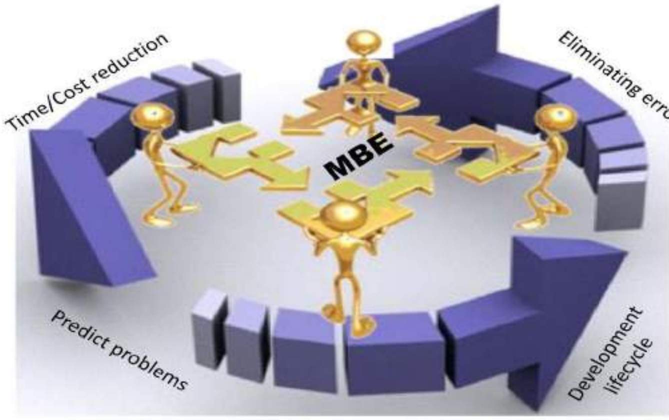

Fig. 1: Model based enterprise as the key influence.

The cost of correcting a defect rises by an order of magnitude at each stage of PCB manufacturing such as if the cost of corrective action is $100 at the design stage, then it may increase to $10000 once the product delivered to the customer [4]. Due to design limitations, electronics manufacturers apply reliability tests following manufacturing the physical prototype, and then refine the product by going back to the design phase and remanufacturing components based on the refinements. This process continues until the PCB meets functional, electromagnetic, thermal, and mechanical requirements. Thus, it is extremely critical for PCB manufacturers to detect failures during design stage. This encourages developing and testing circuit cards virtually to lower, if possible eliminates costly physical prototypes. Organizations should lower the number of physical prototypes and tests, and shorten the time of product flow transferring physical tests to virtual world using advanced modeling, simulation and computation tools. In the past few decades, manufacturing industry has seen many dramatic changes, from computer aided design (CAD) and computer aided manufacturing (CAM) to computer controlled machines and lean processes for assembly. Each of these changes revolutionized the industry in its own way by either decreasing cost, shortening time to market or increasing the quality of the product. Now as moving forward into the next century, a new process of reusing 3D CAD models by all of downstream customers verses recreating or reentering the data it contains is poised to revolutionize the entire lifecycle of a product. This process that replaces a traditional drawing is called **ò**model-based enterprise (MBE)**ó**. This paper responds to limitations of design capabilities of electronics manufacturers to launch prototypes, testing, and refining of products by reducing the need of physical prototype fabrication. In this work, we present a model based enterprise environment, the predictive environment for visualization of electromechanical virtual validation (PREVIEW), which is developed to predict virtual performance of printed circuit boards to lower need for testing labor, decrease the labor cost of manufacturing and nonrecurring costs and shorten the time-to-market. Virtual performance of PCBs is predicted through physics-based simulation tools including thermal and electromagnetic compatibility modules.

This paper is outlined as follow: In Section 2, literature review is presented. Section 3 introduces PREVIEW. Section 4 presents thermal module in PREVIEW and electromagnetic compatibility module is discussed in Section 5. Finally, conclusions are drawn in Section 6.

2 LITERATURE REVIEW

Extensive research has been done to investigate thermal behavior of electronic components and systems. The level of accuracy varies widely in a broad range depending on assumptions and simplifications made. Cheng [6] proposed finite element analysis (FEA) models to solve heat conduction in a microelectronic component. Luo [10] introduced a thermal resistor-capacitor (RC) model for power insulated gate bipolar transistor (IGBT) based on an extraction method that relies on transient thermal impedance from-junction-to-case and transient thermal impedance from-case-to-ambient to determine its parameters. The disadvantage of both tools is that they do not provide a user-friendly tool to the electromechanical designer. An electromechanical designer seeks a tool that enables simulation and validation of various electronic modules with different configurations. A key factor is to provide an automatic methodology that guides the designer to select optimal parameters. An automated tool make is it easy to study different designs and compare them quantitatively. Most software in electromagnetic simulation on the other hand runs in 2D, in which a user can only access limited electromagnetic field information on a circuit [12]. If the user seeks the electromagnetic field precisely in 3D space in an enclosure, he might need to use a high fidelity 3D tool. The major limitation of current software with 3D electromagnetic simulation capability is that there is no available database with component information in the software such as electromagnetic and material properties as well as geometric characteristics. As every time the circuit would be analyzed, each component has to be built.

Many studies have been conducted in both theory and practice in electronic manufacturing [1, 13]. However, most of them were based on 2D analysis and models, which cannot give the opportunity of modeling and simulating the entire product life cycle. Model-based enterprise, as the name implies, utilizes 3D high fidelity models to drive and enable all functions of an enterprise. While many leading manufacturers make extensive use of modeling and simulation tools in their engineering and business processes, model-based enterprise concept represents a sweeping change in the technological foundation, business processes, and culture of the enterprise. It is a manufacturing entity that applies modeling and simulation (M&S) technologies to radically improve, seamlessly integrate, and strategically manage all of its technical and business processes related to design, manufacturing, and product support. By using product and process models to define, execute, control, and manage all enterprise processes, and by applying physics-based simulation and analysis tools to make the best decisions at every step of the product lifecycle. It is possible to radically reduce the time and costs of product innovation, development, manufactures, and support [9]. In the next section, PREVIEW and its capabilities are presented.

3 PREVIEW

Predictive environment for visualization of electromechanical virtual validation is an interactive and immersive 3D environment including predictive physics based capabilities to support virtual testing of PCBs. It enables product designers to assess potential design shortcomings based on virtual physics-based test capabilities, thus reducing the time and cost associated with developing and testing several iterations of prototypes prior to production. This gives a benefit of flexibility and capability to perform a large number of òwhat-if" type computations to explore new material and systems or optimize existing ones in addition to early evaluation of occurrences and analysis of causes, minimize the risk of the flight test activities, simulate hazardous conditions and to evaluate manufacturing process and capacity analysis.

Considering the fidelity and visual representation of circuit boards, PREVIEW is ahead of commercialized software. PREVIEW is unique in that the current state of the art limits circuit board design to a two-dimensional approach, and implements electrical and mechanical designs in separate environment with very limited consideration of the effect of one design upon the other. By extending the design process into three dimensions, allowing the electrical and mechanical designs to be reviewed concurrently, and by employing physics-based modeling and simulation approach, our technology enables many design issues to be identified and resolved prior to prototype development. Besides, PREVIEW enables design engineer to access cost information and material requirement that can be integrated into organizationsʼ enterprise resource planning system. As shown in Fig. 2, PREVIEW also enables one to explode each layer and to work on layer-by-layer, a feature that does not exist any of available commercial products.

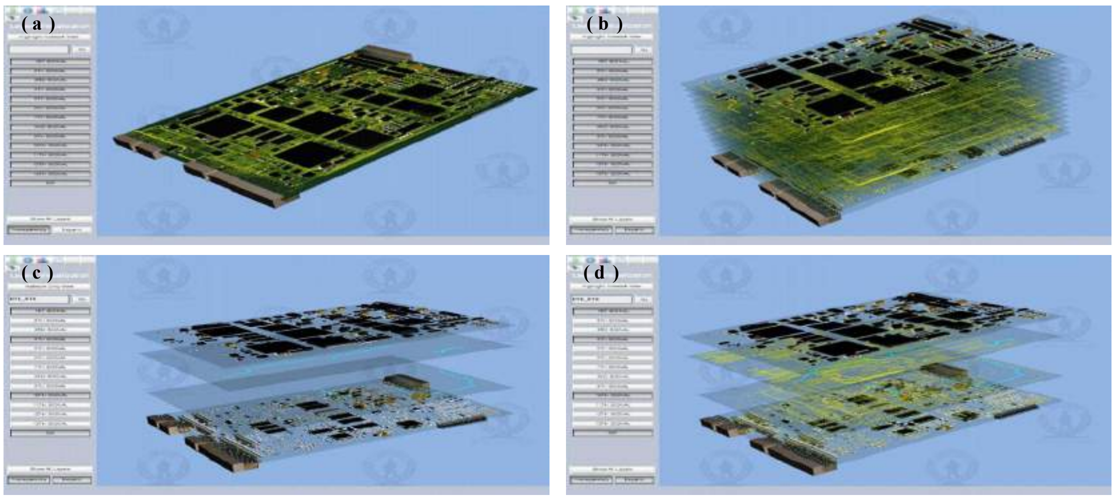

Fig. 2: (a) A PCB with electromechanical components installed, (b) layers stack-up in exploded view, (c) two mid-layers shown without network traces, and (d) two mid-layers shown with network traces.

Fig. 3 demonstrates capabilities of PREVIEW including drafting a circuit card in a mechanical enclosure, virtual testing, accessing reliability and cost data, and component identification. Using PREVIEW, design engineer can draft a circuit card from scratch starting with exporting an enclosure in AP210 step files format and corresponding circuit boards at respective locations inside the enclosure. Next, components are added step-by-step following the assembly instruction in PREVIEW. The other important capability of PREVIEW is virtual testing, which enables design engineer to access circuit card configurations using a multi-meter measuring voltage between two points on a network, current on a point and resistance of a component. By dragging virtual probes (red and black) on different points on a circuit, PREVIEW will update the displayed information interactively. This capability thus assists design engineer in not only placing components on a board, but also configuring the circuit connections. Fig. 3(c) illustrates accessing cost and reliability data information through the developed user interface. All information related to each component can be accessible through the database. PREVIEW can also enable integrating its database into organizationsʼ enterprise resource planning (ERP) systems. Information such as but not limited to reliability data of components including mean life and failure rate, operating conditions i.e. operating temperature range, cost of component, part vendor name, part number and package number is accessible to the user. This feature enables design engineer to search database with better properties or lower cost value so that an ideal replacement component can be easily retrieved. Fig. 4(d) shows component identification in a circuit card design, where components can be graphically displayed that shows the number of components used in the design process. Each component is displayed with a different color allowing the designer to access total cost and reliability information of circuit card easily.

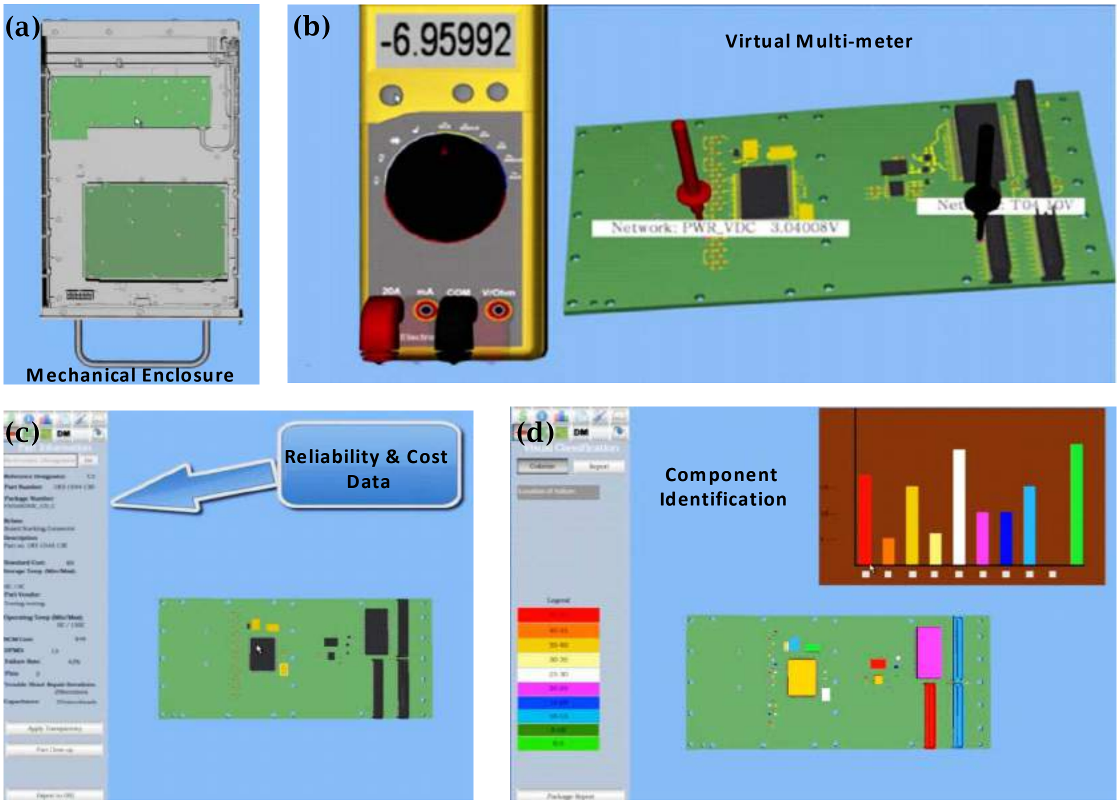

Fig. 3: PREVIEW capabilities: (a) a circuit board in a mechanical enclosure (chassis), (b) virtual multi-meter reading voltage between two points in a network, (c) reliability and cost data, and (d) component identification.

4 THERMAL MODULE

Thermal analysis of PCBs is obtained through the integration of ANSYS Icepak® [2] within PREVIEW. Icepak is commercial software designed to perform thermal analysis of PCBs. The software allows the user to build a printed circuit board with different electronic components such as chips, capacitors, resistors etc. PREVIEW prompts the user to enter the operating conditions and parameters for those components. This includes power input, thermal conductivity, mesh parameter and relevant boundary conditions.

Fig. 4 shows a multiple board assembly placed in a mechanical enclosure. All of the components are selected from a pre-defined objects library. Once all input parameters are taken, PREVIEW sends commands to Icepak® in order to compute the temperature field on the PCB and within the surrounding domain specified by the user. Additional variables can be computed too such as heat flux, velocity and pressure field of air surrounding the PCB assembly.

Geometry with higher accuracy can be defined using CAD files, which are imported in IGES format. An accurate representation of the geometry will lead to a more realistic model that enhances the virtual environment. PREVIEW exports the IGES files by placing them in the project directory which contains the files that Icepak® requires to perform the analysis. These files contain the parameters that define the problem input. A batch file is created by PREVIEW to run Icepak®. PREVIEW is programmed to extract relevant data from Icepak® and display it to the user. One major way is by extracting the nodal temperature data and displaying the contour plot. Location of the minimum and maximum temperatures can be highlighted to allow the user making wise judgments on how to improve the design. These results can be translated into reliability and validity of the design.

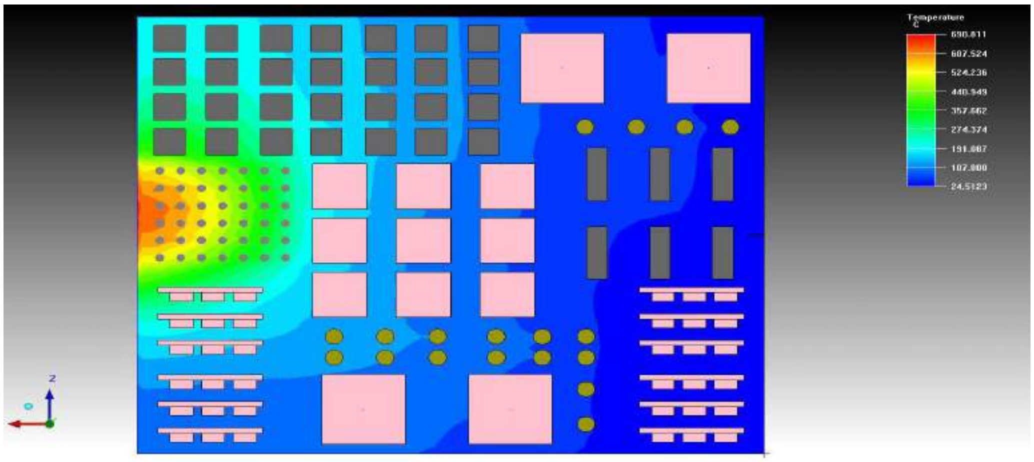

Fig. 4: Top view of temperature contour plot of a PCB assembly.

In this work, component level thermal analysis capabilities are also integrated to PREVIEW. For example, in-house code is developed to compute 3D temperature distribution inside components. The code utilizes a C++ program that applies finite difference method (FDM) to solve a two point boundary value problem. The heat equation in its general form using cylindrical coordinates is as follows [8]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right)+\frac{1}{z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c_p\frac{\partial T}{\partial t} \quad (4.1)$$

$\frac{\partial T}{\partial r}$, $\frac{\partial T}{\partial \phi}$ and $\frac{\partial T}{\partial z}$ represent the temperature gradient in radial, circumferential, and axial directions, respectively. k is the thermal conductivity of the material used. $\dot{q}$ is the heat source term. Temperature gradient with respect to time is represented by $\frac{\partial T}{\partial t}$. ρ and c_p are density and specific heat, respectively. For steady state analysis, which is the case in this study, $\frac{\partial T}{\partial t}$ is set to zero and hence the right hand side of equation becomes zero.

Eqn. (4.1) is a partial differential equation that requires a numerical scheme to approximate the solution with boundary conditions as temperature values. The code is developed further to approximate the temperature distribution for 3D assuming that the temperature gradients in the radial and circumferential directions are negligible. Fig. 5 shows a sample temperature distribution in a 3D resistor. This feature allows user to perform thermal analysis at the component scale which is critical in component based reliability modeling.

In this section, thermal module is presented. Next section introduces electromagnetic interference module within PREVIEW.

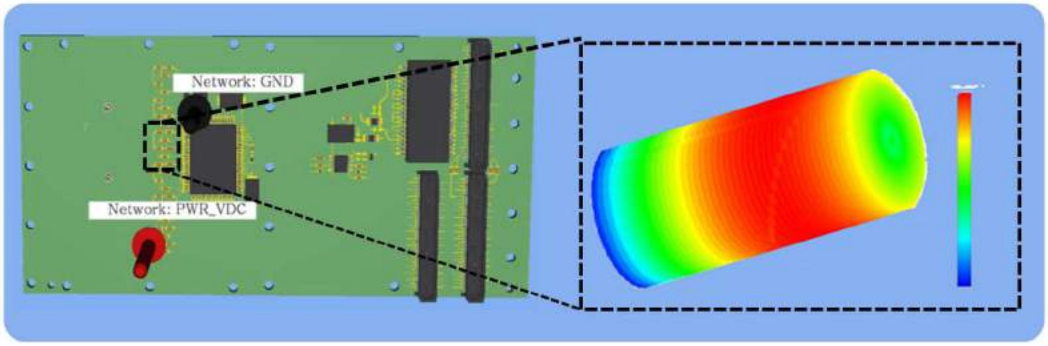

Fig. 5: 3D Temperature contour plot of a resistor.

5 ELECTROMAGNETIC INTERFERENCE MODULE

Electromagnetic characteristic of PCBs are analyzed through the integration of CTS MWS. CST MICROWAVE STUDIO® [7] within PREVIEW, which allows users to import or built circuit boards with 3D components and analysis electromagnetic characteristics through physics-based simulation. Typical operating frequencies and material properties of those components are available in PREVIEW database. The software can analyze electrical field, H field, far field scattering as well as surface current on a circuit.

There are two major issues in electromagnetic compatibility: electromagnetic susceptibility and electromagnetic emission. In general, electromagnetic susceptibility is referred as the victim of external electromagnetic field source. Electromagnetic emission is, on the other hand, resulted from undesired generation of electromagnetic energy by improper grounding, lack of shielding or poor configuration of circuit design. In this paper, both issues have been demonstrated with an example through simulating circuit cards with multiple boards. In electromagnetic emission simulation, a sample circuit is connected to an existing source (either current source or voltage source). Current induced electrical and magnetic fields are simulated in 3D using finite difference time domain analysis. However, in electromagnetic susceptibility simulation, circuit generates uniform electromagnetic field without a voltage source connection. Electrical field and magnetic field can be still available on the circuit board, which are caused by a parasite electromagnetic field source. In practice, both issues should be addressed together.

Fig. 6 shows a current/voltage sourceðfree three-layer board generating a uniform electromagnetic field. Fig. 6(b) depicts surface current simulation resulted from multiple boards. Direction of arrows represents the current direction and arrow color highlights magnitude of the current. It is clear that even if there is no current/voltage source connected on the circuit, current still presents along wires due to an external electromagnetic source. Performance, characteristics and reliability of a circuit card can thus be affected by an external parasite.

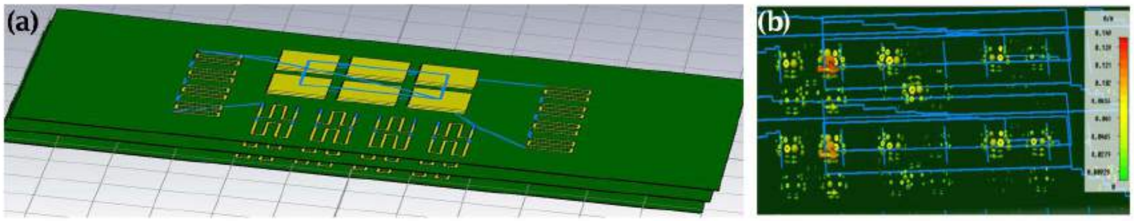

Fig. 6: A multi-board PCB electromagnetic susceptibility example with the surface current simulation result (f= 1G Hz).

Fig. 7, on the other hand, illustrates a three-layer board electromagnetic emission example, where the chassis is placed in an electromagnetic field-free environment. The red spot on the circuit represent a 15V voltage source. Fig. 7(b) depicts electrical field simulation result of the circuit in -z direction, where frequency is 1GHz. Fig. 7(c) shows y-z cut-away plane of the simulation in ðz direction. Although multi-board configuration has three layers with same layout, components and network configuration, generated electrical field results differ considerably while electromagnetic emission generated by each board affects the others. This can be however alleviated by applying shielding around the emission source. PREVIEW also enables user to define shielding characteristics on component level and assist electromechanical designer to investigate possible ways to reduce emission.

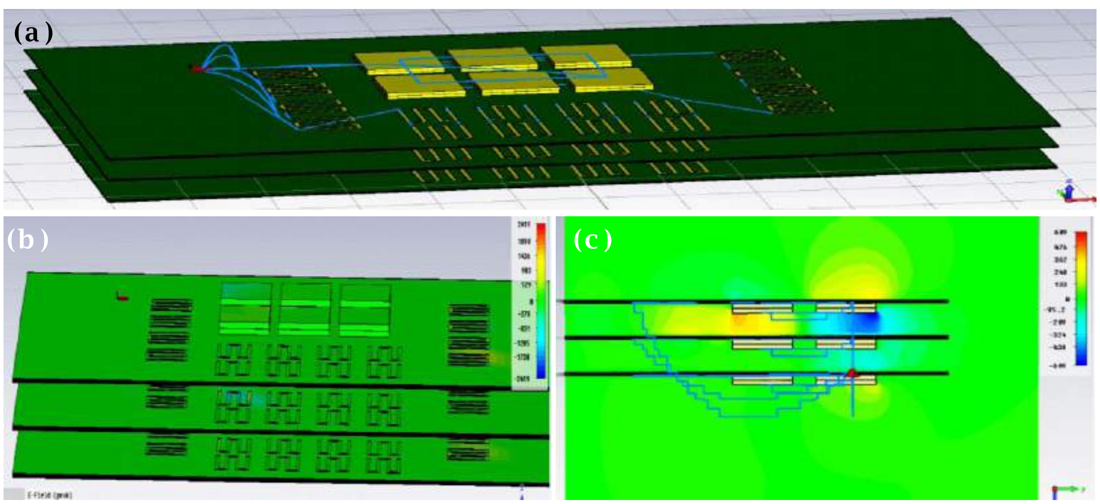

Fig. 7: A multi-layer board electromagnetic emission example with the electrical field simulation result in z direction (f= 1G Hz).

6 CONCLUSIONS

In this paper, model-based manufacturing has been applied for electronics design and testing through development of a virtual environment, PREVIEW, in support of virtual performance of printed circuit boards. PREVIEW enables electronics packaging designers to assess potential design shortcomings based on virtual physics-based test capabilities, thus reducing the time of decision making and lowering the cost associated with developing and testing several iterations of prototypes prior to production. PREVIEW assists electromechanical design engineer to access various capabilities such as thermal and electromagnetic performance in component, board, multiple boards and enclosure level as well as cost and reliability data. Besides, it guides design engineer to draft a circuit card from scratch following assembly instructions. For future work, we will attempt to model, develop and integrate thermal shock and vibrational shock modules, which are major sources of circuit card failure in electronics manufacturing.

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