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PCB DESIGN FOR THERMAL RELIABILITY

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In recent years the PCB computer aided design industries have spent a considerable amount of effort in the development of sophisticated tools for schematic capture, component placement, electrical simulation and routing. However, except for some thermal analysis programs, thermal reliability design concepts have not been integrated into the design process. PCBs must be designed to withstand the heat dissipated by the components in the environment in which the PCB resides. This requires that not only the tools for thermal design and analysis be in place, but that there is also a means to predict and correct the design for thermal reliability.

PCB DESIGN AND RELIABILITY

The layout of a PCB affects electrical, thermal and mechanical engineering conditions as well as routability. Examples of electrical layout considerations include minimizing the total wire length on the PCB, clustering functionally related components to conform to speed and transmission line requirements, keeping analog and digital components separate to reduce crosstalk, etc. Thermal layout considerations typically include conforming to thermal and thermal reliability constraints for individual components and meeting the allocated system failure rate or system mean time between failures (MTBF). Mechanical layout considerations include geometric conditions for manufacture and placement for vibrational and thermo-mechanically induced stresses.

Presently, because of the complexity of modern PCB designs consisting of hundreds of components, PCB layout and in particular the placement of components has become a task which is extremely time consuming and involves difficult decision making which is often beyond the expertize of a design engineer. To help the design engineer, computer aided design (CAD) techniques have been developed. For example, a number of programs are available to automatically place components on a PCB to minimize the total wire length. Unfortunately, such programs typically neglect placement based on other measures such as reliability.

Reliability prediction is fundamental to system design. It involves the quantitative assessment of a systems reliability prior to development. Reliability predictions provide criteria for reliability growth and demonstration testing, maintanability, supportability and logistic cost studies. Up-front reliability prediction in the electronic design process can result in a reduction in the design lag time and a savings in the total cost when calculated over the lifetime of the product. It is therefore important that estimates generated from the prediction techniques be accurate enough so that design tradeoffs and design decisions can be confidently determined. If the reliability analysis provides a conservative prediction, overdesign can occur. This can result in higher costs. On the other hand, a falsely optimistic evaluation can lead to catastrophic results and should always be avoided.

THERMAL RELIABILITY AND FAILURE CONCEPTS

With an increase in component density and with the move to VLSI, components have been dissipating more heat. Heat dissipation per component typically ranges from 0.01 - 0.4 W in SSI devices, 1 - 5 W in LSI ECL and VLSI CMOS devices, and to more than 20 W in some VLSI ECL devices. Furthermore, the trend towards packages which use surface mount technologies, enables more components to be placed closer together on a PCB. As a result, thermal reliability has become an important design issue.

Thermal failure is defined as the thermally induced total loss of electronic function in a component. Temperature induced failure can result from melting, vaporization of a part of the component, thermal fracture of a support or separation between leads. The maximum allowable component temperature can be found in manufacturers' catalogs or military specifications. Checks must then be made to insure that the temperature of the component in the PCB environment is sufficiently below this value.

Failure can also occur from prolonged use at elevated temperatures. The results may be a gradual change in the material properties, creep in the bonding material, parasitic chemical reactions in connectors and switches, and diffusion in solid state devices. The general rule of thumb is that for every increase of 20 C of a component, the failure rate doubles.

The operating temperature of an electronic component is dependent primarily on the heat dissipation of the component augmented by heat losses by the surrounding components. Component temperatures are dictated not only by inherent performance requirements but also by stringent reliability demands. This is especially true in military and avionic electrical equipment where high reliability is a critical factor and insight into the most efficient cooling system parameters is necessary.

DESIGN FOR THERMAL RELIABILITY

Design for thermal reliability requires that the temperature of the components, in the operating environment can be measured or predicted. Presently, there exists a variety of numerical thermal analysis programs to analyze complex second and third level packaging configurations. These programs typically use finite element or finite difference techniques to solve a nodal representation of the circuit layout.

The degree of thermal interaction among components depends on the associated cooling mechanism and operating parameters. Electronics are cooled by three methods: conduction, convection and radiation. A common conduction cooling mechanism utilizes a cold plate embedded in the PCB. Here, heat is dissipated through external heat sinks located at the edges of the PCB. As a result, the innermost components will be hotter than than the external heat sink temperature. This type of cooling is used in many areospace applications where convection cooling is too bulky and costly. Conduction cooling is often analyzed as a two dimensional resistive network of interacting components.

Convection cooling utilizes the flow of a fluid such as air to cool the devices. Natural convection usually does not remove enough heat for reliabile operation. For forced air cooling, the heat flow may be treated in terms of a resistive network with component temperatures predominantly dependent only on those components which are upstream in the air flow.

Radiative cooling is important only when conduction and convection are not used or when components are in close proximity to another surface. For a standard electronic module (SEM) which uses a cold plate cooling, radiative cooling accounts for less than 1% of the heat loss.

Once a cooling system is introduced and a thermal analysis which includes the interaction of components is completed, a more accurate measure of the reliability can be obtained. As a result, parameter selection and tradeoff studies pertaining to the cooling mechanism, reliability, maintainability and performance as well as life cycle costs, can be accomplished.

In 1982, the "RADC Thermal Guide for Reliability Engineers", published by Rome Development Center, estimated that a heat transfer specialist with at least five years of experience needs one week to do a 20 node model of a printed circuit board and two weeks for a 70 node model. Recently, more efficient programs, which make use of sophisticated computer aided design and engineering techniques, and interdisciplinary data bases, have been developed to increase thermal reliability design productivity. In fact, models with up to 2,500 nodes can now be automatically generated and a thermal and reliability analysis executed in under an hour on a personal computer.

THERMAL RELIABILITY PREDICTION

In the design of digital electronics, there are a number of handbooks, specifications and guidelines which must be followed. When and how these are used in the design and evaluation process dramatically affects life cycle performance, scheduling, costs and supportability. For example, the MIL-HDBK-217E presents two reliability prediction techniques used by the military and based on theoretical and statistical concepts: a parts count analysis and a parts stress analysis. The use of a particular technique depends on the design stage and available design data.

In the parts count analysis method, an estimate of reliability based on a part type (resistor, capacitor, transistor, integrated circuit, etc.) is determined. In this analysis, the component attributes and functionality, location and electrical interconnection with other components on an electronics assembly do not affect the reliability. This method provides a "bucket" type analysis which is applicable during the proposal and early design stages where the amount of detailed data is limited. The advantage of this method is that it allows rapid estimation of reliability to determine the feasibility (in terms of reliability) of the design approach.

A more complete accounting of a component's attributes and working parameters and it's electrical and mechanical relationships with other components on the PCB are included in the failure rate calculation provided by the parts stress analysis. Since detailed component parameters are utilized in the analysis, this method should give more accurate results than the parts count analysis. For these reasons, the parts stress analysis is typically only applied during the later stages of the design evaluation process. This is not necessarily desirable since the design time can be greatly increased if a design change is required as a result of the analysis.

In order to get a measure of the results obtained from the reliability prediction methods, a PCB design containing a mix of 59 SSI through VLSI digital micro-electronic components in addition to resistors and capacitors was selected. The board was designed for conduction cooling through a cold plate. A parts count analysis, a parts stress analysis at various environmental temperatures and a detailed parts stress analysis at various heat sink temperatures was executed. The chosen environmental factor corresponded to an airborne uninhabited fighter which has associated with it an environmental temperature of 95 degrees C. Additional environment (heat sink) temperatures included were 80, 60, 40 and 20 C.

Table I presents a summary of the data obtained from the tests. The total failure rate was calculated under the assumption that the the total failure is the sum of the component failure rates. The MTBF is then calculated as the inverse of the total failure rate.

TABLE I

MEAN TIME TO FAILURE (HOURS)
ENVIRONMENT : AUF

Parts Count Analysis (PCA)	17,863
Parts Stress Analysis (PSA)	
Case temperature :	
95 C	5,828
80 C	11,625
60 C	29,317
40 C	66,330
20 C	112,148
Parts Stress Analysis (PSA)	
Heat sink temperature :	
95 C	4,653
80 C	9,130
60 C	22,971
40 C	53,880
20 C	99,601

It is apparent that reliability prediction depends on the information available. Since the detailed parts stress analysis which includes thermal interaction effects simulates reality best, this is the desired prediction method.

DESIGN METHODS

To utilize the detailed parts stress analysis up-front in the design process, it is possible to use a database of representative components selected in a manner similar to that prescribed in parts count analysis, but with more detailed information. For example, the engineer may determine that 50 resistors, 80 capacitors and 70 integrated circuits will comprise the components for a given size electronics assembly. If this is the extent of the information, then components with attributes representative of typical components in each category are distributed onto the PCB workspace and a thermal and reliability analysis are executed. Typical information includes the technology type, size, number of pins, average heat dissipation, etc. The process is very similar to the development of a cost program for bidding a PCB design project.

As additional component information is obtained, the component values are progressively updated and the thermal and reliability analysis are executed again. This approach gives the designer a current and accurate reliability prediction based on the known and estimated information.

If a design does not meet allocated reliability requirements, there are a variety of methods which are used to upgrade the reliability: the cooling system can be improved, redundancies can be added, and components can be re-arranged so that sensitive components can be placed in cooler locations. Improving the cooling system by lowering the external heat sink temperature or the input air flow temperature, adding heat sinks, etc. is the best approach as long as cost, size, weight and the possible decrese in reliability of the cooling mechanism is considered. Adding redundancies is a means to improve reliability if there are only a few unreliable components and extra space is available on the PCB or assembly.

Relocating components is the best option when a 10 - 30 % gain in reliability is needed. Different arrangements of components on a PCB affect a variety of different guidelines and requirements as well as the reliability expressed in terms of the failure rate. However, the authors believe that while minimizing the failure rate may not be the approach to take, a design compromise may provide results which satisfy all the design requirements if appropriate design trade-offs are employed through a sensitivity analysis.

Figure 1 shows the results of a study [5] conducted on the effects of component placement on the reliability and routability of a densely packed six layer PCB used in aerospace applications. Four cases consisting of different component placements were investigated. Case I was an industry designed PCB placed according to traditional routing and thermal guidelines. Case II was placed using a CALAY autoplacement routine. Case III was placed to maximize the reliability and in Case IV, sensitive components were placed for reliability and the remaining components were autoplaced. Figure 1a shows the failure rate of the PCB in failures per million hours. Figure 1b shows the number of vias and Figure 1c gives the total printed wire length. Each PCB was routed to 100% completion in a day.

It is very interesting that the autoplacement routine did not necessarily minimize the total wirelength, and that an improvement of approximately 36% was gained by thermal reliability management over the traditionally designed PCBs.

REMARKS

The demand for higher reliability of more complex designs places a added burden on design engineers. An assembly consisting of components with reliabilities which are individually acceptable may have a poor reliability when a large number of such components make up an assembly. Thus, the reliability of an assembly depends on the complexity as well as the reliability of its components.

Some related studies and articles written by the authors are given below. They present more detailed accounts of many of the concepts discussed here.

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