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# Design for Reliability of Printed Circuit Boards

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# DESIGN FOR RELIABILITY OF PRINTED CIRCUIT BOARDS
## "A Mechanical Engineering Perspective"

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## SUMMARY

A well designed product satisfies performance requirements and optimizes between reliability, producibility, supportability and cost criteria. In the design of electronics, these design criteria originate from a variety of disciplines. Electrical criteria include meeting signal distribution, power distribution, board I/O, and grounding rules, reducing crosstalk, and minimizing routing track lengths to meet speed and transmission line specifications. Environmental criteria include meeting environmental derating limits. Mechanical criteria involve designing for durability under vibrational and thermal-mechanical loading. Manufacturing criteria include meeting geometric constraints for quality control, and providing acceptable assembly conditions.

While computer aided design (CAD) techniques have been developed to handle some of the complex electronic design tasks such as logic simulation and routing, the design process remains highly labor intensive, demands a significant amount of process flow time, and involves difficult decision making. Techniques must now be developed to provide decision support and optimization capabilities to meet all design criteria.

The University of Maryland Computer Aided Life Cycle Engineering (CALCE) research effort is involved in developing system level techniques to optimize electronic designs with respect to the general Unified Life Cycle Engineering (ULCE) design goals of performance, producibility, reliability, supportability, and life cycle costs. The approach consists of the application of design criteria through the application of interactive heuristic and algorithmic design optimization techniques.

Early efforts focused on integrating thermal analysis and thermal related reliability constraints and design rules into the design of printed circuit boards, using computer-aided design (CAD), and decision support (DS) techniques. As a result of that effort, part of the CALCE system, called RAMCAD [2,3] has been introduced into the Westinghouse Defense Electronics Center design process for thermal evaluation of circuit boards in the Airborne Self Protection Jammer (ASPJ radar). In the past year, a variety of CAD, DS and artificial intelligence (AI) tools, design techniques and test procedures have been developed for reliability management and thermal-mechanical stress-strain and vibrational analysis, and have been introduced into the RAMCAD system. These efforts are currently being broadened to include a distributed support system for ULCE design.

This paper discusses some of the design, analysis, modelling and prediction issues addressed by RAMCAD. The focus is on up-front computer-aided design for reliability of printed circuit boards for digital electronics from a mechanical engineering perspective.

## DESIGN FOR RELIABILITY

Design for reliability provides criteria for reliability assessment, growth and demonstration testing, maintainability, supportability and logistic cost studies. Up-front reliability analysis and prediction in the electronic design process has been shown [9-15] to increase the product performance over time, provide a reduction in the design flow time and offer a savings in the total cost when calculated over the lifetime of the product. It is therefore important that reliability estimates be accurate and timely so that design tradeoffs and design decisions can be confidently and effectively made.

A varity of design for reliability techniques can be introduced into the CAD design process. Several of the more important approaches utilized in PCB design are discussed below.

Preferred parts selection is a method whereby parts (components or circuits) are chosen from a database of parts which have tested and acceptable reliability for a given mission environment. It is assumed, generally based on field data, that such parts are capable of withstanding the stresses for the proposed mission.

Derating is a technique by which either the stresses acting on a part are reduced or the strength of a part is increased, in correspondence to critical environmental stress factors. The methodology behind derating depends on the part type. For example, semiconductors are derated by maintaining the power dissipation below a rated level. Capacitors are derated by maintaining the applied voltage below the rated part voltage. Resistors are derated by maintaining the ratio of operating power to rated power below a fixed value.

Thermal management involves the selection of the cooling technology and the associated parameters. For example, if the heat dissipation per unit heat transfer area is known, the designer can select an appropriate cooling mechanism, assuming that the added cost, size, weight and the possible decrease in reliability of the cooling technique are acceptable. Cooling parameters can then be bounded by examining the limiting component temperatures dictated by inherent performance and reliability requirements. Parameter selection is then conducted using tradeoffs based on optimization studies. For example, if the design parameters associated with a forced convection cooling mechanism have been bounded, the designer can then select the flow rate, fin structure and inlet temperature design parameters by conducting tradeoff studies of these parameters as a function of the system failure rate or MTBF. Tradeoffs can then be extended to the assembly level. Altoz et al. [16] presented a methodology for the allocation of forced air cooling resources for PCB assemblies.

Once the components, cooling mechanism and cooling design parameters have been chosen, layout of the PCB can be initiated. A variety of layout strategies which consider reliability issues have been presented in the literature [1,4,8,10,12,13]. The reliability can also be improved by adding redundancy if extra space is available on the PCB or assembly, and if other constraining conditions introduced from the added power requirements, heat dissipation, fanout, etc. are meet.

As with other design processes, layout requires that design and manufacturing constraints are not violated. Figure 1 shows the results of a tradeoff 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 different component placements were investigated. Placement I was an industry designed PCB placed according to traditional routing and thermal guidelines. Placement II was placed using a CALAY autoplacement routine, which has as its primary objective the minimization of wire-length. Placement III was placed to maximize thermal reliability and in Placement IV, a few sensitive components were placed for reliability and the remaining components were autoplaced. Figure 1 shows the failure rate of the PCB in failures per million hours, the number of vias, and the total printed wire length, for each placement.

PCB design for reliability also centers around determining the location and magnitude of stresses on critical parts, such as solder joints, vias and connectors. An estimate of the fundamental mode of vibration can be calculated early in the design process based on the board dimensions, an uniformly distributed weight, and simplified boundary conditions. This gives the designer a base line resonant mode shape of the PCB. Then, given the PCB transmissibility and the loading conditions, the dynamic bending stresses can be calculated and the expected areas of maximum deformation can be located. This estimate can be improved once electrical and non-electrical components are discretely placed, a finite element mesh generated, and boundary conditions which more closely reflect those of the actual circuit board fixture within the electronics assembly are applied. Supporting mountings, ribs and stiffners can then be incorporated into the design where applicable.

Upon completion of the proposed layout, stresses arising from coupled thermal, vibrational and shock loading, covering the complete range of potential conditions based on field data and predicted events, must be evaluated. Loading conditions which arise from indirect events such as cyclic deformations due to in-plane thermal expansion mismatch, cyclic and transient thermal loading conditions, and loading due to temperature and time dependent nonlinear material and metallurgical properties, must also be considered.

Once the analysis is complete, areas on the PCB showing high thermal gradients and/or high deformation gradients should be identified. The effects of failure critical effects such as thermal mismatch, solder joint fatigue, stresses on thin vias, etc. can then be analyzed in detail and in conjunction with specific fatigue and fracture models. This may require that statistical failure models be introduced if the failure modes cannot be easily combined.

## RELIABILITY MODELLING FOR PREDICTION AND DESIGN

In the design of digital electronics, handbooks, specifications and guidelines aid in the design and evaluation process. When and how these are used can dramatically affect life cycle engineering criteria. For example, Pecht and Kang [5] investigated the effects of different MIL-HDBK 217E reliability prediction methods on typical PCB designs used in aerospace (uninhabited fighter environment) applications assuming convective cooling. The prediction methods included a parts count analysis, a parts stress analysis at various environmental temperatures excluding thermal interaction effects and a parts stress analysis which included thermal interaction effects. Simulations were conducted at inlet temperatures of 20, 40, 60 and 80 degrees C. It was shown that deviations up to 20% can arise in the prediction by excluding the thermal interaction effects, and that the parts count analysis was not a good predictive measure for reliability.

All prediction techniques depend on the modeling functions and associated parameters. Error bounds must be well understood, especially when nonlinear functions or non-monotonic functions are used in modelling. Furthermore, the effect of inaccurate data introduced into tradeoff routines which apply multi-variable optimization techniques must be understood.

Reliability models are important for reliability prediction, but are most useful if they can be used to generate a beneficial design change. To accomplish this, models must address the failure modes of the devices as a function of the history dependent material properties, the geometry, and the loading conditions.

An important issue in modeling is the extent to which a particular failure phenomenon can be independently modeled, predicted and tested. In general, lumped parameter statistical approaches have been applied to electronic failure mechanisms because of the large number of failure variables, the difficulty of independently testing the effects of the variables, and the lack of failure specific constitutive equations with which to write equations to model modes of failure. Unfortunately, such models restrict design improvements by covering the causes of failure.

In general, the mechanical engineering approach to failure modeling involves determining the specific failure mechanisms in terms of stress-strain, fracture or fatigue models which are tied to vibration, shock, and thermal loading conditions. This can aid the designer in predicting and improving the causes of failure. For example, as a result of a mechanical analysis of the solder joint fatigue on the PCB, the number of power cycles can be predicted and the materials comprising the component package and the PCB can be subsequently matched. However, even here, tradeoffs must be considered. Ceramic PCBs, especially thick films, can be manufactured with a thermal coefficient which matches hermetically sealed DIPs and flatpacks. The disadvantage is that such boards are expensive and have a very high dielectric constant which can cause electrical problems. Another solution to the thermal mismatch problem is to use compliant solder tails to avoid cracking resulting from thermally induced fatigue and fracture. The disadvantages of using solder tails include the additional use of board space and the extended component profile.

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# BIOGRAPHIES

Michael Pecht received a MS in Electrical Engineering and a MS and PhD in Engineering Mechanics from the University of Wisconsin, Madison. He has consulted on the NASA ASTRO I space telescope on finite element fracture analysis. He has also conducted research with Westinghouse Defense Electronics and with the Institute for Defense Analyses on a variety of electronic packaging design issues. Dr. Pecht is presently an Assistant Professor in the Mechanical Engineering Department at the University of Maryland where he heads up the University of Maryland CALCE project. He has over 50 publications and is a member of IEEE, ASME, AAAI, IEPS and IPC.

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Joseph Naft is Director of the Computer-Aided Design Laboratory of the Engineering Research Center of the University of Maryland. He is responsible for providing guidance within the College of Engineering on the development of its CAD program and for Maryland companies on the selection and implementation of CAD systems. Mr. Naft is also a consultant to the Institute for Defense Analyses of Alexandria, VA. for whom he has performed research into the design of a RAMCAD workstation, a Unified Life Cycle Engineering design environment, and decision support for design optimization. Prior to joining the University, Mr. Naft was an engineering group leader for the Boeing Co. where he was involved with Computer Aided Design. Mr. Naft holds a B.S. in Aerospace Engineering from Case Western Reserve University and an M.S. in Physics from Vanderbilt University.