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Advanced Product Realization Through Model-Based Design and Virtual Prototyping

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Introduction

We use the term "product realization" to refer to the entire product and process realization cycle, beginning with concept identification and tradeoff, continuing with design, development, and production, and ending with stockpile maintenance and eventually disposal. Several government agencies and industrial sectors have recognized the need for, and payoff of, investing in the methodologies and associated technologies for improving the product realization process. Within the defense community as well as commercial industry, there are three major needs. First, we must reduce the **cost** of military products, of related manufacturing processes, and of the enterprises (complexes and/or industrial bases) that have to be maintained. Second, we must reduce the **time** required to realize products while still applying the latest technologies. Finally, we must improve the **predictability** of process attributes, product performance, cost, schedule and quality. We must continue to advance technology, quickly incorporate our innovations in new products and in processes to produce them, and we need to capitalize on the raw computational power and communications bandwidth that continues to become available at decreasing cost. Rapid prototyping of testable and verifiable hardware, software and manufacturing processes, in both virtual form and in physical form, will be an essential element of our success. In many cases, we would like to sell the first hardware that is produced.

A Sandia National Laboratories initiative is pursuing several interrelated, key concepts and technologies in order to enable such product realization process improvements: model-based design; intelligent manufacturing processes; rapid virtual and physical prototyping; and agile people/enterprises. While progress in each of these areas is necessary, this paper* only addresses a portion of the overall initiative. First a vision of a desired future capability in model-based design and virtual prototyping is presented. This is followed by a discussion of two specific activities -- parametric design analysis of Synthetic Aperture Radars (SARs) and virtual prototyping of miniaturized high-density electronics -- that exemplify the vision as well as provide a status report on relevant work in progress.

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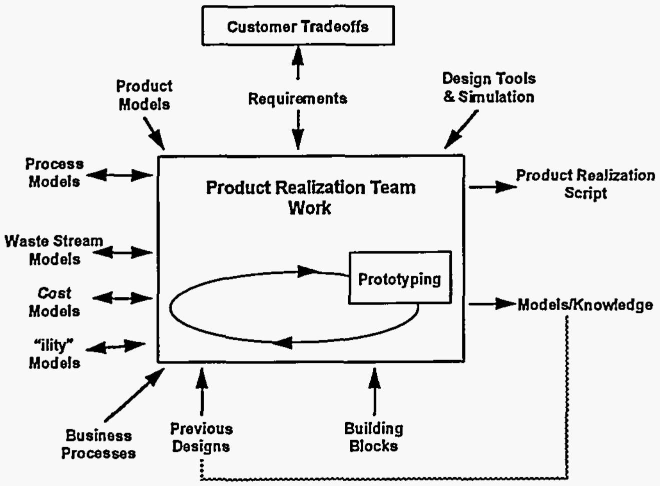
Model Based Design

The fundamental notion of model-based design is to capture knowledge about products and processes in validated, parametric, computerized models and to embed these models in an integrated design environment as shown below.



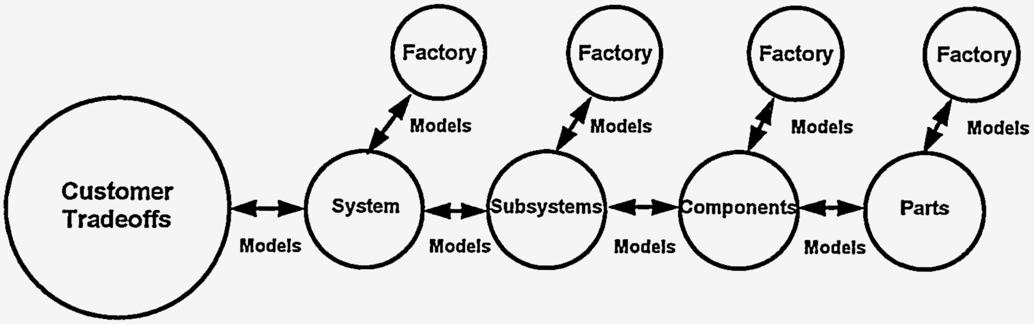
Within this environment a Product Realization Team (PRT) performs a design, prototype, and iterate cycle. The structure exploits modeling and simulation and permits fast design iterations to be performed on the computer, thus reducing cycle time and requiring less build and test. Furthermore, the build and test that is done is not only to insure the quality of a point design but also for the purpose of verifying models. This is the process by which the enterprise expands the knowledge base and continually improves the process. The suite of design concerns in this environment is broad and includes such aspects as manufacturability, reliability, maintainability, cost, business practices, waste stream concerns, and the like. The models used here are not only essential to design but also underpin the entire product realization process as they can be used as the basis of product verification during manufacture and in use or in stockpile. A key benefit of this process is its support of rapid trade-off and what-if cycles, the purpose of which is to achieve a balanced design. A balanced design is one in which most if not all of the design aspects have been "optimized" as a group. This is in stark contrast to current design practices. Often one or two key design aspects (e.g., performance) are optimized at the expense of many other elements of the design (e.g., manufacturability).

The PRT is guided through the process by computer-based intelligent agents which continually infuse the process with knowledge gained from the enterprise's previous experiences and lessons learned. Rapid iteration in the design environment, highly concurrent product and process design, reuse of knowledge and lessons learned to avoid repeated mistakes, and a full life cycle view of product realization dramatically enhance the affordability of both products and processes. The resulting environment is an ever growing, ever learning entity which becomes increasingly more valuable as it matures.

A key characteristic of the above concept is that it is fractal, that is, it may be applied to systems, subsystems, assemblies, or devices. It may be applied for products, for manufacturing processes, or for an integrated product/process design. When applied to a specific product family in particular, and with qualified and verified models, the above structure represents a parent space that can launch variant designs called child designs. The space contains all of the fundamental attributes of the product and processes, their statistical variations and their interrelationships. Once the parent space is in place, child designs can be developed rapidly and in many cases somewhat automatically. Furthermore, there is a very high assurance of the product's manufacturability attributes as each point design or child has a genealogy that is traceable to the knowledge base or parent.

Because the process is fractal, it is applied at all levels of a system hierarchy and its model-based nature provides model-based linkage between elements, as shown below. One of the highest leverage points in the entire product realization process is during the early stages of system or product design when tradeoffs are made, requirements are set, and product and process approaches are established. This is one of the areas in which this process is particularly valuable by bringing additional information to the level of the hierarchy where the decisions are being made. Information moves about the hierarchy in the following way.

Model Based Design



The hierarchy as described here, embodies both a top down and bottom up view of the product being designed. As shown, this hierarchy also identifies the contribution of the production processes at each stage. As one proceeds down (left to right in this figure) the hierarchy via decomposition, the information takes the form of tentative requirements. These requirements are effectively performance models (for that level of assembly) that increase in detail. As one proceeds up the hierarchy, the information takes the form of integration as models are abstracted and simplified into higher levels. This model simplification is an essential element of increasing the scope of the simulation at higher stages of the hierarchy. Without this reduction effort, the available computing resources would quickly become inadequate for the size of the problem to be simulated. The interfaces are linked through an object-based information architecture. The effect of changes at any level can be captured and understood. This is essential for performing rapid tradeoffs and the generation of balanced requirements and designs.

Where does the future of model based design point? There appear to be at least two significant development areas in which the model-based design concept should expand. The science that underpins product models and process models coupled within the understanding of material failure modes leads to the exciting promise of predictive reliability. In this case, materials models, manufacturing process effects and statistical variations are combined with virtual prototyping and test to yield a capability to consider reliability issues early in the design. Model validation with product surrogates such as assembly test chips is an essential element of the approach. Emerging design tools that help a designer tradeoff system architectures from the standpoint of reliability (mean time between failure, etc.) early in design will truly improve the product realization process. The second development area is that of co-simulation. In the real world there are often interactions between the various multiple physical environments (e.g., thermal, mechanical, etc.). Just as designers routinely measure electrical or mechanical performance at temperature extremes, the simulation environment needs to address those needs also.

Rapid Virtual and Physical Prototyping

A prototype is a model, a representation, or a sample of a product or a process and may be virtual or physical. The term “rapid prototyping” is often used to describe techniques such as stereolithography or selective laser sintering used to fabricate mechanical product prototypes from 3D solids models. In this paper, the term is used more broadly and we concentrate on virtual (computer-based) prototyping of both products and processes.

In general, prototypes serve a number of important uses. They are used in tests to verify that a product design meets its performance requirements, to increase understanding of the solution space and to help develop parametric characterization of tradeoffs. When computer models and/or other predictive techniques are used in the design process, physical prototypes can validate such models for the particular product design at hand as well as for variant designs that extend the solution space and may be needed in the future. They are used to evaluate product innovations, to obtain customer feedback or market evaluation, and to aid in negotiating requirements with customers.

The computer models used to guide the model-based product design and enable intelligent manufacturing processes form the basis for rapid virtual prototyping. Virtual prototyping is the application of these modeling and simulation tools to the examination of product performance and testing in a computer simulation environment. All operational scenarios in both normal and abnormal conditions can be examined quickly through the use of computer simulations. Individual component models are combined to provide system level representations to examine the interactions and interfaces of multiple components and subsystems. Individual intelligent manufacturing processes are coupled to the design/performance simulation so that the designer can examine the ability of the distributed enterprise to produce the desired product within the desired cost and schedule. The availability of fabrication resources can also be examined. Virtual tests are performed through simulation by exercising product and process operating parameters and examining electrical, structural, thermal, etc. responses to varying inputs and environmental conditions. Since this is done in the computer, virtual prototyping iterations are performed very rapidly and impacts on design can be identified quickly.

An important result of virtual prototyping is the identification of specific physical prototyping needs. Some virtual prototyping and testing will identify areas requiring additional information available only through build and test. Rapid physical prototyping will be carefully targeted to answer specific questions which when coupled with the broad virtual prototyping activities described above will provide comprehensive product and process performance information. Since a goal of this physical prototyping to validate and provide information to the virtual prototyping models above, it need not examine all possible product and environmental configurations. Once rapid physical prototyping and test has been performed, the resulting information is used to improve the computer models underlying the virtual prototyping environment so that even less physical prototyping is needed in the future. Thus the effect of virtual prototyping is not to eliminate the need for physical prototyping, but, rather to reduce the amount of physical prototyping and significantly increase the amount of quantitative information which is gained from each physical prototype which is tested.

Once the PRT is satisfied with the results of the rapid prototyping, the knowledge of the fabrication processes captured within the virtual prototyping environment is used to automatically generate the production scripts which orchestrate the on-floor fabrication processes. These production scripts (e.g., electronic travelers) are compiled and sent to the resources within the distributed enterprise to coordinate the diverse fabrication resources in an integrated manner and to provide a complete paperless audit trail for quality assurance. It is important that the same models used to simulate and evaluate alternative fabrication processes be used to drive the actual process machines within a distributed fabrication enterprise. This insures maintenance of a link from the final product fabricated to the science and knowledge base used to predict product performance and reliability. Without this direct link, predictive approaches to small lot, high reliability product realization cannot be accomplished. Insertion of unmodeled activities into the fabrication process creates uncertainty and reduces the power of model-based approaches to predict reliability.

The realization of the vision described above is certainly a long term activity; however, significant portions of this vision have been and/or can be accomplished using tools, methods, and compute engines which are currently available today. The following two sections exemplify some of the concepts described above.

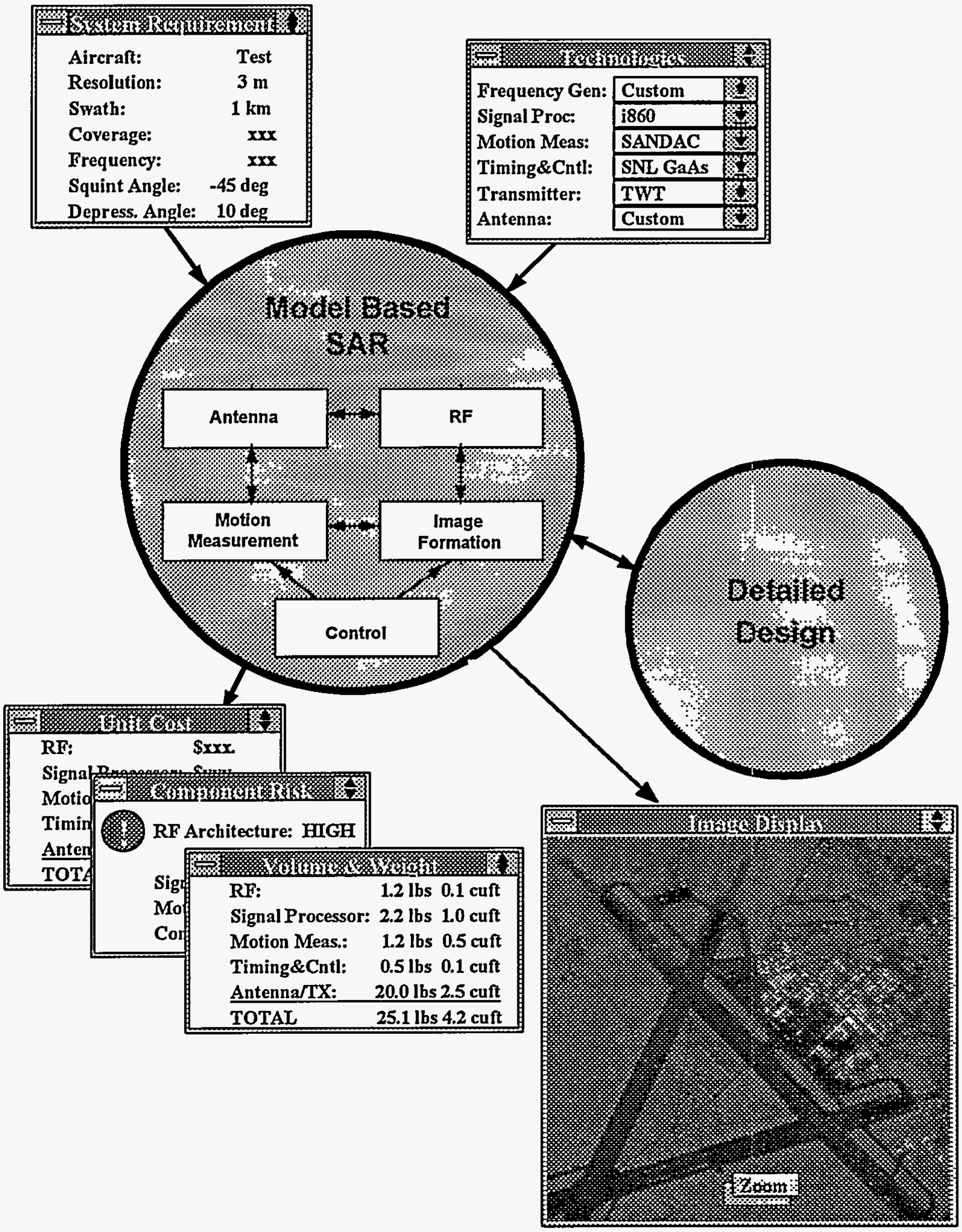
Parametric Design Analysis of SARs

In many product realization efforts, the majority of the final production cost (weight, program risk, etc.) is determined or committed to in the very early stages of the project. These determinations are often driven by very high level decisions which are sufficiently decoupled from the design details. Although it is necessary to make high level decisions without supporting design details, any information which can be used to quantify the impact of these high level decisions would result in a more informed decision. One way to try to help decision makers in this process is to apply parametric analysis.

Parametric design analysis is a powerful practice that facilitates the rapid analysis of affordability and the rapid realization of product. At the heart of this technology is an in depth understanding of the product or process's solution space. What are all of the fundamental attributes of the product or process? What is their statistical variation? How are they interrelated to the other product attributes or process variables? Once these detailed understandings have been gained, this suite of knowledge defines a parameter space which is called the "parent space". Subsequent designs which fall wholly or mostly within this qualified space, benefit from this previous work. That benefit comes in the form of reduced development times, reduced cost, reduced risk, etc.

An example of the use of parametric characterization at Sandia is in SARs. About 300 interrelationships within a SAR's parameter space that relate to component and subsystem performance to system performance have been characterized in a spreadsheet. At a subsystem level a more detailed model (an associated simulation tool) for using multiple, commercial i860 signal processing boards in SAR image formation has been developed. A user friendly interface that allows SAR designers to rapidly optimize the number of i860 boards for given performance requirements has been provided. An example output is shown below.

Model Based SAR Design



System Requirement

Aircraft:	Test
Resolution:	3 m
Swath:	1 km
Coverage:	xxx
Frequency:	xxx
Squint Angle:	-45 deg
Depress. Angle:	10 deg

Technologies

Frequency Gen:	Custom
Signal Proc:	i860
Motion Meas:	SANDAC
Timing&Cntl:	SNL GaAs
Transmitter:	TWT
Antenna:	Custom

Unit Cost

RF:	$xxx.
Signal	
Motio	
Timin	
Anten	
TOTA	

Component Risk

RF Architecture: HIGH

Sig
Mo
Co

Volume & Weight

RF:	1.2 lbs	0.1 cuft
Signal Processor:	2.2 lbs	1.0 cuft
Motion Meas.:	1.2 lbs	0.5 cuft
Timing&Cntl:	0.5 lbs	0.1 cuft
Antenna/TX:	20.0 lbs	2.5 cuft
TOTAL	25.1 lbs	4.2 cuft

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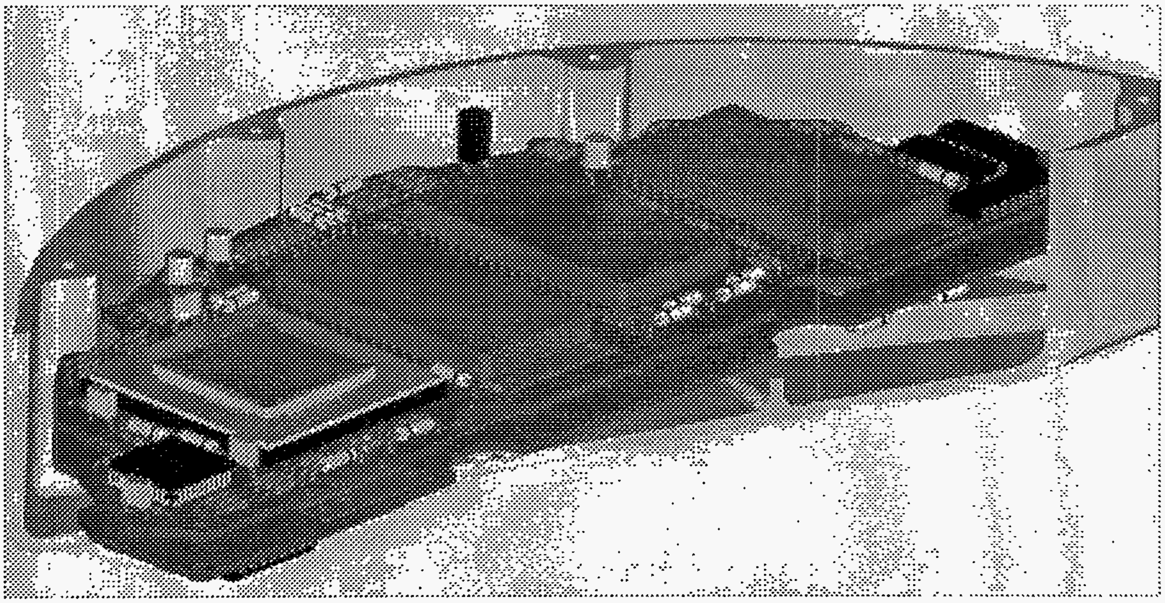
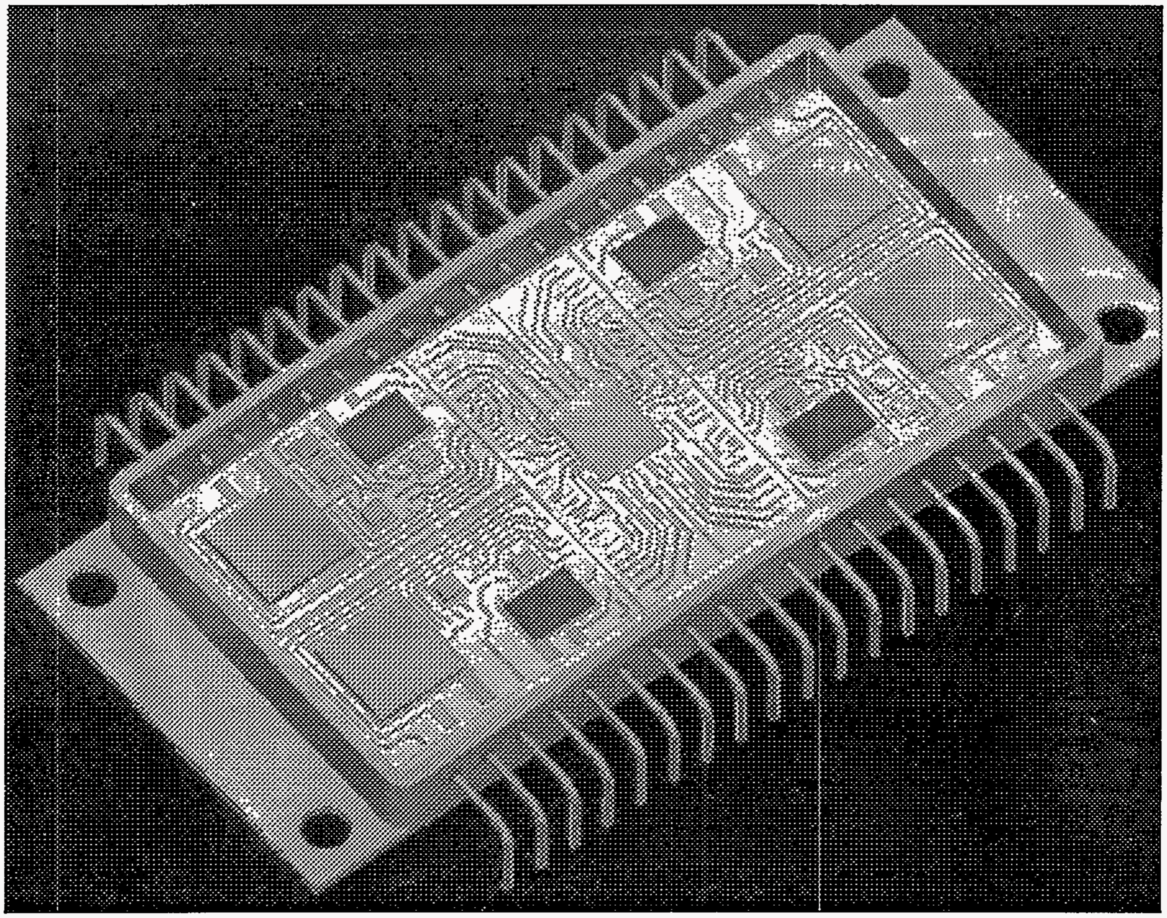
Virtual Prototyping of Miniaturized High Density Electronics

Electronic product designers are faced with increasingly greater challenges as the size of electronic products are reduced and the density of electronics within that volume increases. This challenge takes the form of additional interaction between the thermal, electrical, and mechanical aspects of the design. The analysis required to support these dense high performance designs places significant demands upon the computer simulation environment but offers a corresponding potential payback on the investment. In order to identify both the analysis needs and the potential value of such analysis a virtual prototype of a specific piece of miniaturized weapon hardware was constructed and evaluated.

A relatively simple piece of hardware was selected so that the focus of the effort would be on the essential elements of the simulation and its benefits rather than on problems associated with memory requirements and execution times. Military systems, as do commercial products, benefit from the integration and miniaturization of electronic products. At Sandia recent efforts have focused on miniaturizing and modularizing electronic "building blocks" for some of the core weapon components. This effort resulted in the design of a family of approximately 1" by 2" multi-chip modules (MCM's). From this family of modules, a virtual prototype was constructed for the output module from a Modular Adaptable Controller (MAC) based weapon programmer design.

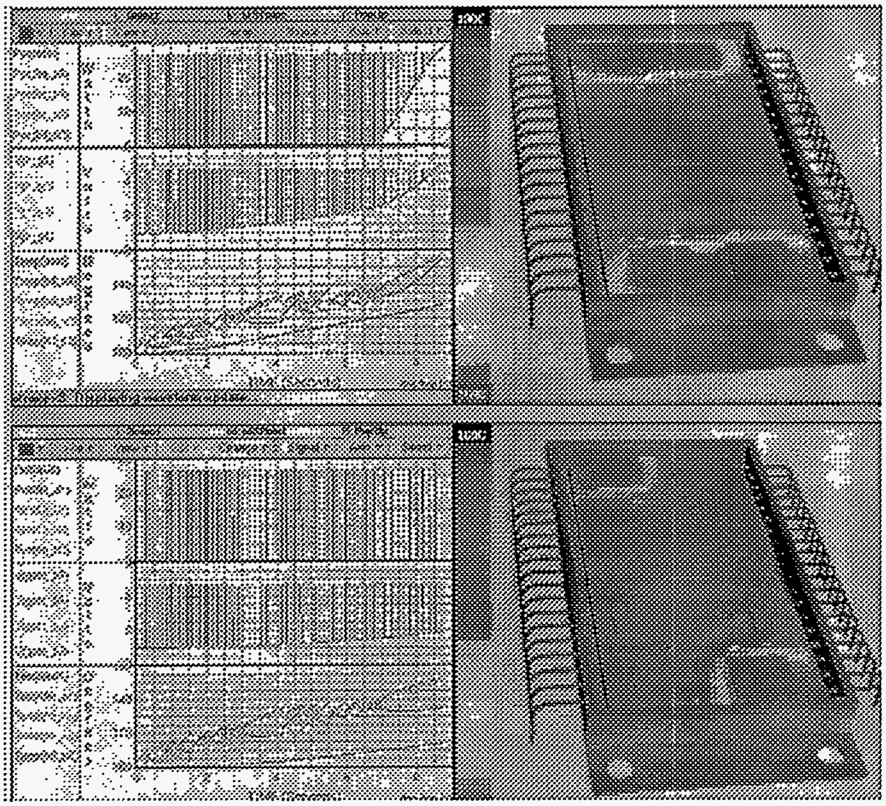


The output module consists of eight power MOSFET transistors and an analog level-shifting ASIC. The design of this analog ASIC was done using a commercial vendor process and simulation models. The goal of this work was to determine the complexity and value of both the mixed discipline (electrical-thermal) simulation and the production process simulation. The mixed discipline simulation was accomplished by taking the solid model of the candidate design and using that to create a finite element mesh of the entire module. This virtual prototype employed an electronic circuit model, a 3-dimensional solids model, and a 46,000 element thermal mesh.

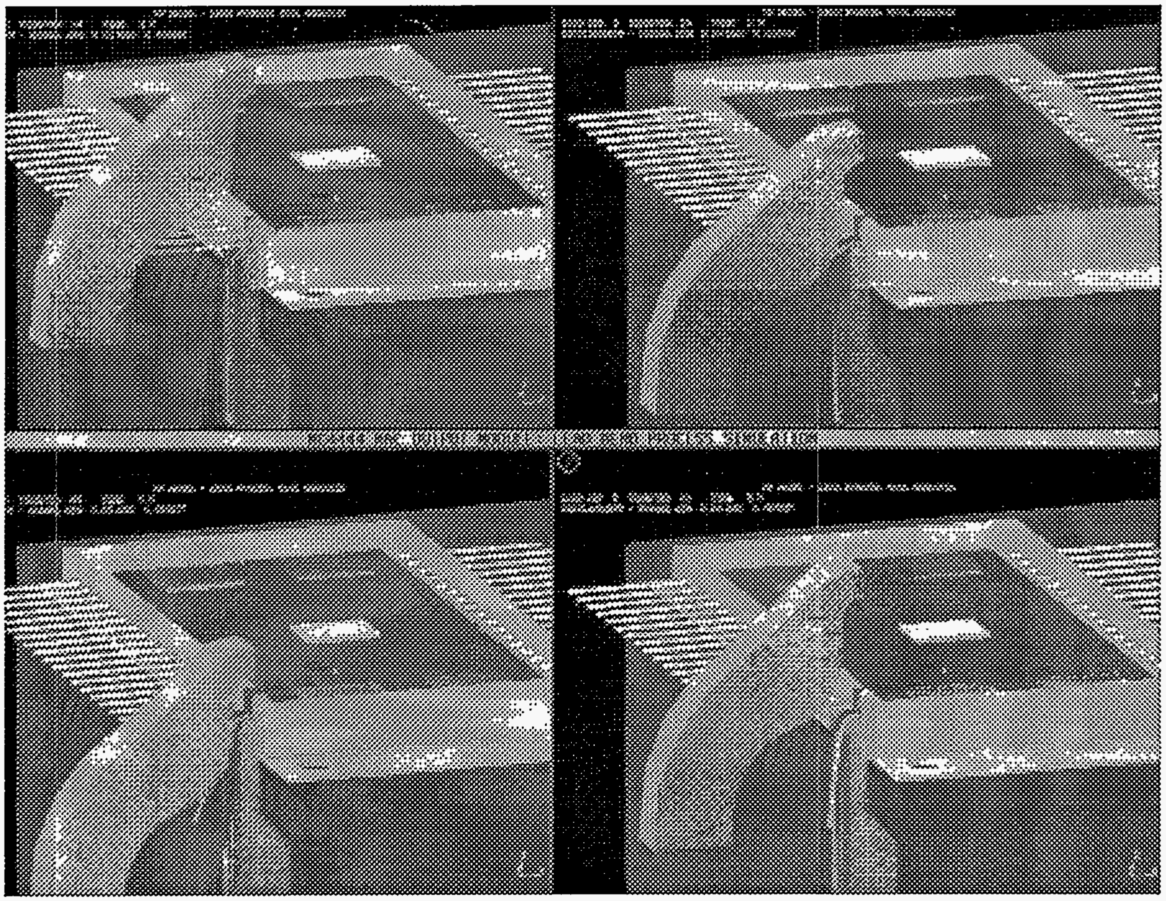


The mixed discipline analysis was accomplished by two separate analysis packages; a finite element thermal transport code, and an electronic circuit simulator. The co-simulation was accomplished by taking the Sandia and commercial codes and loosely coupling their execution. This analysis provides the data necessary to study the thermal management issues. Within this simulation environment the effect of various ambient temperatures, pulse duty cycles, material selections, and fabrication processes were evaluated. This coupled simulation predicted the circuit behavior in reaction to the internally generated heat over an eight second operational lifetime. This virtual prototype allowed quantitative evaluation of alternative fabrication options vs. electrical performance and/or design margin. The figure below shows a snapshot of the dynamic temperature distribution on this MCM. Note that the power FETs in the corners of the MCM are the primary source of heat in this assembly. From the corners heat flows toward the center and ultimately raises the temperature of the analog ASIC to the point where electrical performance requirements are not met.

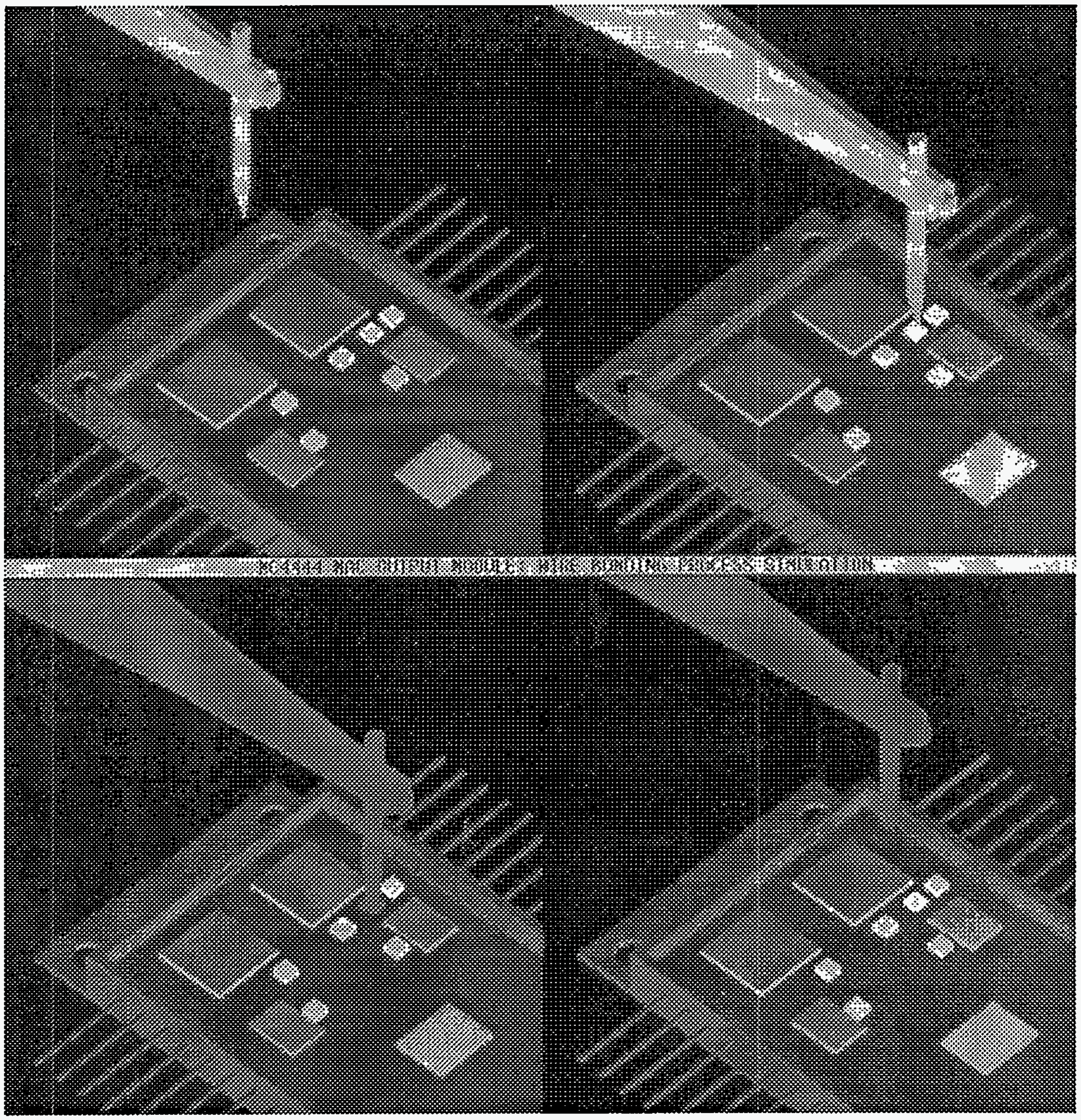
Trade-off analysis were performed with this virtual prototype which verified that multiple substrates would sufficiently isolate the sensitive analog ASIC from excessive heat generated by the power devices. By separating the MCM substrate into multiple pieces the heat transfer to the center piece (which contains the ASIC) was reduced.



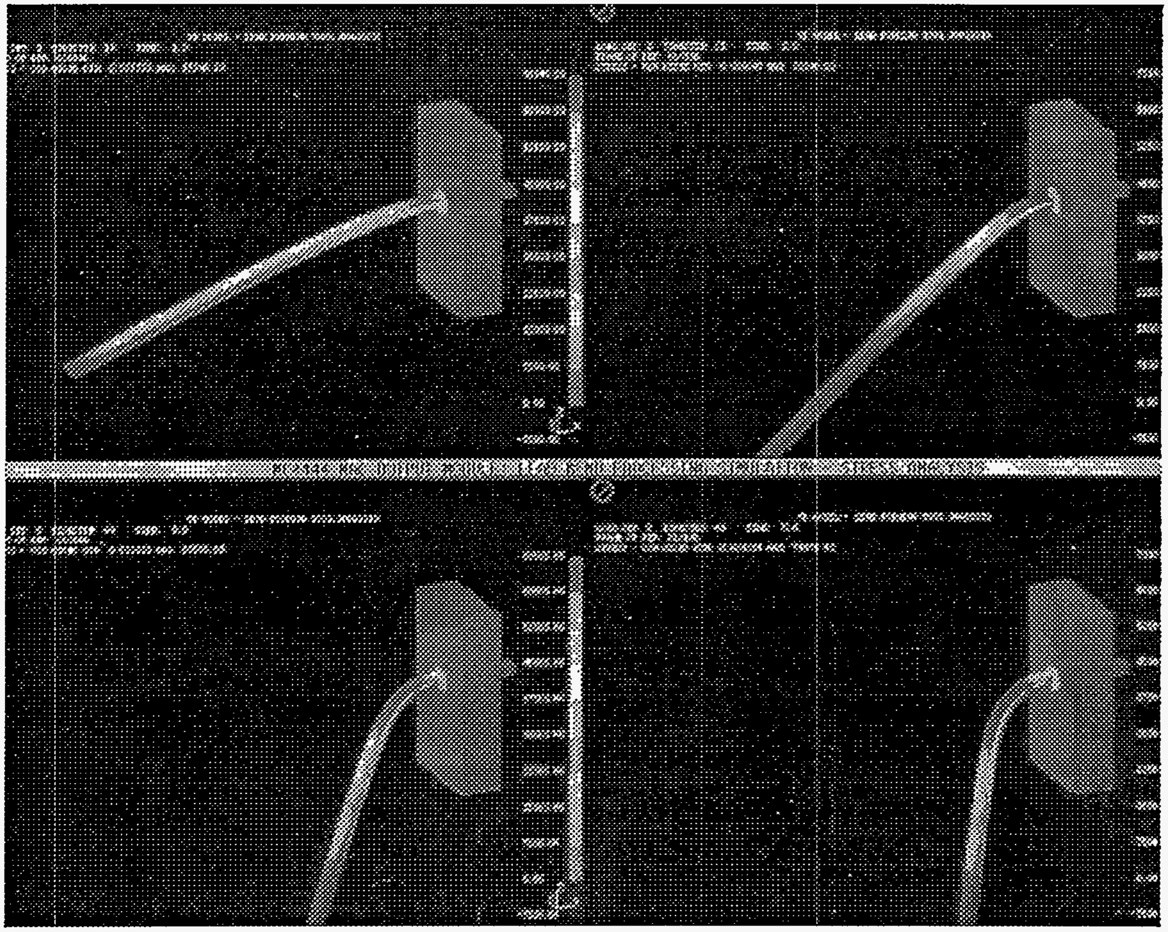
A secondary result of making this change, however, was that the ultimate temperature of the FETs increases and that added expense would be incurred due to the inter-substrate wire bonding. To address some of the production-related issues associated with this MCM, Sandia and Allied Signal/KCD collaborated on the analysis of this additional wire bonding. A kinematic model of the wire bonding was created. This model will serve as the beginnings of a process modeling capability in which the machine controls can be debugged and/or optimized prior to the existence of actual hardware. The value in this capability is both a decrease in the design cycle time (concurrent development) and providing inexpensive means of debugging machine programming data without risking expensive hardware.



In addition to the wire bonding process, an analysis was performed which addresses design rule evaluation and checking. The MCMs are often mounted on both sides of the circuit board to increase circuit density. The issue regarding the capability of the production agency to reliably form the lead radius for these parts was also a consideration. A kinematic model of the lead forming process was created and evaluated. Within the model the effect of the tooling on a specific lead radius was evaluated quantitatively.



This kinematic model fed a finite element analysis. This analysis calculated the anticipated stress in the MCM leads due to the forming process. This stress is a crucial indicator of the integrity of the glass to metal seal on the MCM package.



All of the results (models and data) generated by such analyses can be assimilated into the knowledge base to support future designs. Sandia has on-going projects which will expand upon this work by coupling in additional areas of analyses such as electromagnetic, thermal-stress, mechanical, etc., and by applying these methods to higher levels of system definition. Virtual prototyping of electronic products such as this MCM enables significant advantages to the product realization effort. The ability to quantitatively establish product performance and the added concurrency of product and process design are perhaps the most notable. Additional benefit is gained in the area of design capture and model reuse.

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