

CHAPTER 2

DESIGN

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ABSTRACT

The purpose of this chapter is to review the existing capabilities that may be used to design parts that will be micromanufactured without lithography-based processes. In the past five to 10 years, non-lithography-based meso- and microscale (NLBMM) parts have seen increased use in medical applications, consumer products, defense applications, and several other areas. These technologies promise to have an impact on the economy, improve health and safety, raise our standard of living, and form a middle-scale stepping stone by which the benefits of nanotechnology may be accessed. The technologies used to design NLBMM parts and the processes and equipment used to fabricate them are in a nascent stage. These technologies have been, for the most part, borrowed from the design practices of macroscale engineering and very large-scale integration (VLSI). At present, most designers have difficulty ascertaining the appropriate time to use pre-existing design knowledge, theory and tools. Designers must be able to assess the suitability of pre-existing technology for the design of NLBMM parts. Otherwise, design processes will be long and iterative, with the result that the products' benefits will be either delayed or lost. As designers, *we must understand the nature of this new technology and work hard to generate the design knowledge, theories and tools that will enable the widespread and rapid advance of NLBMM technology.*

Given the nascent state of NLBMM technology, this chapter focuses on the technologies that “should be.” Some of these technologies may be borrowed or adapted from the macroscale and VLSI design domains, whereas others will have to be fundamentally different. This chapter aims to explain the aspects of NLBMM parts design that are fundamentally unique and the circumstances in which these unique differences call for new design knowledge, theories and tools. Toward this end, this chapter contains discussions on the following topics: (1) the reasons why unique requirements exist for the design of NLBMM parts, (2) the existing knowledge and practices that may be borrowed to design NLBMM parts, and (3) the gaps between existing technologies and the requirements for NLBMM part design. The topics are arranged so that members of disparate design communities (e.g., decision theorists, hardware and mechanical designers, design theorists, industrial designers, and process design specialists) may make use of the knowledge gained during this study.

THE APPROACH TAKEN TO ASSESS THE STATE-OF-THE-ART IN NLBMM DESIGN

To assess the state-of-the-art in NLBMM design, the first step is to understand the fundamental differences between traditional design technologies and design technologies that are needed to support the design both “of” and “for” NLBMM components. This distinction is made here to accommodate the disparate and polarized design camps that support either:

1. The “design of,” meaning the design of specific machines, equipment, software, and other devices; or

2. The “design for,” meaning general technologies that support design theory and process.

The needs of NLBMM design span the interests of many design communities. The assessment conducted in this chapter takes a balanced approach, concentrating on design knowledge that is considered important by most design communities. Great effort has been expended to construct the chapter so that (1) it has value to members of many design communities and (2) the members of the different communities will understand the need for collaboration among the different communities. Although the focus of this chapter is on technical challenges, it is important to note that the low level of collaboration between the different design communities is a primary barrier to solving the general problem of NLBMM design.

UNIQUE REQUIREMENTS FOR THE DESIGN OF NLBMM PARTS, PROCESSES AND EQUIPMENT

Designers need to know why NLBMM design is different from macroscale design and they need to understand the fundamental reasons for these differences. Figure 2.1 shows a generic representation of a multi-scale system in which distinct parts (e.g., rectangles) are grouped according to characteristic size scale. The reason for examining a multi-scale system will become apparent in a moment. The different-scale parts are coupled to other parts via cross-scale links. In general, these links may be characterized as (1) function/performance links; (2) form/geometric links such as physical interfaces, (3) flows of mass, momentum, or energy; (4) physical phenomena that govern mono- and multi-scale behaviors; and (5) fabrication and integration constraints. Some of these links are material in nature (e.g., physical interfaces) and others are non-material (e.g., the compatibility of parts fabricated by different processes).

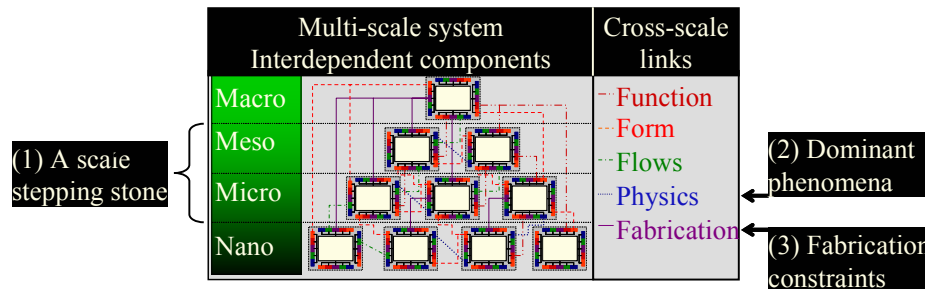


Figure 2.1. Multi-scale system with cross-scale links between components.

The uniqueness of NLBMM parts may be traced to the elements of Figure 2.1 that are highlighted by keyed arrows:

Stepping Stone for Characteristic Size and Time Scales

The microscale is perfectly situated as a “stepping stone” between familiar large-scale technologies and emerging nanoscale technologies. In many cases, the benefits of the nanoscale cannot be realized at the larger scales without the help of microscale components that link the larger and smaller scales. Microscale components therefore occupy a unique position within the scale hierarchy and this position is a critical link for the future utilization of nanoscale technologies.

Meso- and microscale parts are often integrated with parts of different scale, thereby coupling the design of the meso- and microscale parts to the requirements and constraints of parts from different scales. The coupling is particularly important when size and time scales of the meso- and microscale parts differ significantly from the scales of the macro- and nanoscale parts with which they will interact. To some extent, packaging may address the interfacing of different-size parts, but this is a half-measure and not a general solution. Packaging works well for VLSI devices and microsensors, but this approach is not particularly well suited for devices that must share moving mechanical interfaces with parts and devices of other scales. Other size scale issues exist; for instance, situations arise wherein the ratio of a part’s minimum feature size to the grain size approaches unity. This issue significantly affects performance that is not accurately captured by traditional, macroscale modeling and design techniques. Temporal scales are also an issue. For example, the

orders of magnitude mismatch in time constants between different scales. These and many other issues point to the need for a new design perspective in which length and temporal scales are critical for determining the approach to designing small-scale parts and multi-scale assemblies.

Dominant Physical Phenomena

The nature of the physical phenomena that dominate the behavior of components generally changes between the meso- and microscales. As such, the behavior of meso- and microscale components within multi-scale systems may be governed by a mix of different physical phenomena. Engineers and researchers who work in the microscales have learned that the physical principles governing part behavior are dependent on part size. For instance, the dominant physics that govern the behavior of a meso- or microscale part may be electrostatic forces. For a geometrically similar macroscale part, the dominant principles that govern behavior may be linked to body forces. This has several implications for the design of NLBMM parts and systems. First, the general design of the parts may require design tools capable of multi-physics modeling. Second, the need to interface and/or integrate microscale parts with parts of a different scale may require multi-scale modeling tools to predict system-level behavior. Both implications point to a need for a departure from traditional macroscale design models and simulation tools.

Fabrication

Fabrication processes are often scale dependent. For instance, traditional macroscale techniques such as milling are not generally applicable at the nanoscale. Likewise, the nanoscale processes used by nature to build biological systems are not generally applicable to the fabrication of some large-scale parts. The range of utility for a specific fabrication process generally terminates within the meso- or microscale. This is an important point for designers to realize; designers must “design for” compatibility of microscale parts with parts that were fabricated using a macro- or nanoscale fabrication processes. Microelectromechanical systems (MEMS) and very large scale integration (VLSI) designers encounter this issue in the form of packaging challenges.

The link between design and manufacturing has led to design for X (DFX) methods (Boothroyd et al., 1994) and concurrent design practices (Syan and Menon, 1994) that are used to help designers select appropriate design-fabrication process combinations. Although the general idea of DFX and concurrent engineering may be considered scale-independent (the design of parts to be made with fabrication processes that are cost and/or time appropriate), the implementation of these practices depends upon the fabrication processes that are to be used. The small-size scale of NLBMM parts makes it necessary to use new or adapted versions of existing manufacturing technology. As a result, new DFX rules will be needed to help designers make design-process choices that ensure scale-specific manufacturability and cross-scale compatibility.

THE DESIGN PROCESS AND THE IMPORTANT ELEMENTS OF DESIGN OF/FOR NLBMM PRODUCTS

At the most basic level, “design” is a process that is used to generate, evaluate and select a solution for a given problem. There are several approaches to engineering design; creative concept design followed by deterministic modeling (Slocum, 1992), decision making in the presence of risk and uncertainty (Hazelrigg, 1998, Hazelrigg, 1999), robust design (Taguchi and Subir-Chowdhury, 2004), six-sigma methods (Creveling et al., 2002, Yang and El-Haik, 2003), axiomatic design (Suh, 1990, Suh, 2001) and complexity theory (Suh, 2005), customer-centered product and industrial design (Ulrich and Eppinger, 2003), and systematic design approaches (Pahl and Wolfgang, 1999). For the purposes of this assessment, the details of a given approach are less important than an examination of the technologies and processes that are needed to support the practice of design. This section is devoted to (1) developing a design framework that most design communities can understand and agree upon for the sake of discussion, (2) relating this framework to the specific challenges in the design of NLBMM parts, and (3) acting as a segue to the subsequent section, which covers the state-of-the-art (SOA) and the gaps in design knowledge, theory and tools.

Most design approaches utilize the combination of steps shown in Figure 2.2.

2. Design

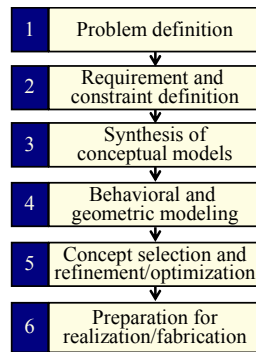


Figure 2.2. Primary steps that are generally followed during design.

The knowledge and approaches taken in steps 1, 2 and 5 have traditionally been independent of specific problems. At the end of this assessment, the author has yet to find a reason that this should change for meso- and microscale parts. The unique characteristics of NLBMM parts (e.g., scale, physics and fabrication processes) are clearly linked to steps 3, 4, and 6; and therefore the technology gaps are associated with these steps. To make this link clearer it is important to develop a shared understanding of the elements that are important to NLBMM design. These elements are independent of the design “school of thought” held by the different design communities. Figure 2.3 shows a triumvirate of elements that are necessary for most design processes. The triumvirate is divided into the following categories:

1. *Multi-scale/physics design knowledge*—The knowledge of physical phenomena that describes the behavior of elements within particular concepts or designs. The knowledge described here extends beyond the realm of the scientific. Design knowledge consists of basic and applied knowledge that may be used in combination to enable one to create a useful and realizable design. This knowledge forms the starting point for generating the concepts (step 3) and forming the models (step 4) that link customer and design requirements with design performance.
2. *Simulation and modeling tools*—Design tools that help designers link knowledge with the requirements of specific concepts/designs. Modeling and simulations tools are used to generate and assess first-order concept models (step 3) and to optimize designs. These tools provide the information that is used to make design decisions.
3. *Design theory and design process*—The approach taken to guide the application of the acquired knowledge and the modeling tools in the formation and optimization of design concepts. This category covers a range of issues that are important for ensuring that parts have been properly designed. The approach includes the selection of overall system/part architecture (e.g., coupling and complexity), consideration of stochastic issues (e.g., risk, and how this applies to engineering decision making), design rules (e.g., DFX and best practices) and a vernacular that designers, manufacturers, and others may use to “converse” with each other (e.g., standards).

Figure 2.4 shows how the design process, driven by design requirements, draws upon an existing base of design knowledge and then uses modeling and simulation tools to process this knowledge and generate designs. Designers must understand all aspects of the triumvirate in order to manage the transformation of design knowledge into a good design.

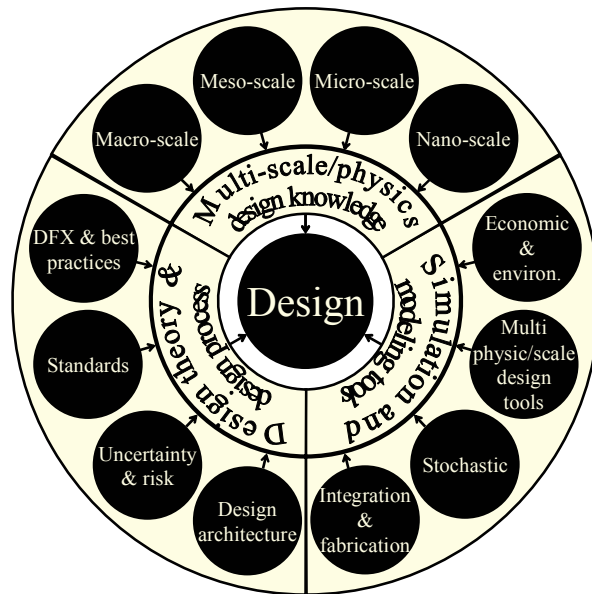


Figure 2.3. Design triumvirate and example elements within each triumvirate.

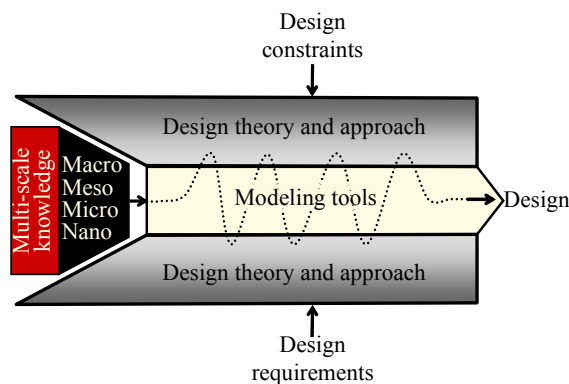


Figure 2.4. The knowledge, theory, modeling, design transformation process.

While the process shown in Figure 2.4 is well developed for most macroscale design domains, it is fairly undeveloped for NLBMM design. The undeveloped state of NLBMM design is due to a mismatch between the nascent state of the technology and the length of time required for design researchers to learn of, and then contribute, to this new field. At present, most designer researchers have yet to learn of this new field. As such, the elements required for the design of/for NLBMM parts are far from fully developed. During the foreign site visits and two workshops, the panelists noted little evidence of substantial efforts that are aiming to address the unique design requirements of NLBMM parts. Most approaches are borrowed from VLSI or macroscale design and then modified to enable engineers to “make a design work.”

THE STATE-OF-THE-ART AND GAPS BETWEEN EXISTING AND REQUIRED CAPABILITIES

This section utilizes the generic design process (Figure 2.2), the design triumvirate (Figure 2.3) and the knowledge-theory-modeling-design transformation process as a basis for discussing the design technology gaps. Herein is provided a comparative assessment of the state-of-the-art in the U.S., Europe, and Asia. Based upon this assessment, recommendations for improving the SOA are tendered to the global design community. Due to the nascent state of NLBMM technology, most of the areas shown in Figure 2.3 have yet to be researched with specific focus on NLBMM applications. As such, the reader will find that the recommendations of this chapter map with high correlation to the elements shown in Figure 2.3.

U.S.-Europe-Asia Comparative Assessment

Figure 2.5 shows a comparative assessment of the SOA in the design of NLBMM parts. Grading is based upon a five-star system in which five stars represents technology that is well-suited to most design applications. For instance, achieving five stars in “multi-scale/physics design knowledge” indicates that the technology is mature and suitable for most applications. A five-star rating does not indicate a full understanding has been achieved. Given the nascent state of NLBMM technology, ratings with a quantitative foundation cannot be provided. This assessment reflects the opinions of the primary author formed using information obtained via the site visits, literature search and the U.S. workshops. More information was available to assess the SOA in Europe and this may have led to the slightly higher grades for that region.

Countries			
Activities	Europe	Asia	US
Multi-scale/physics design knowledge	**	**	**
Design theory and process	**	*	*
Modeling and simulation tools	**	*	*

Figure 2.5. Comparative assessment of worldwide efforts in the design of/for NLBMM products.

Regardless of the limitations, the results of the assessment indicate that the SOA in technologies that support the design of/for NLBMM parts is far from ready to provide adequate support for designers. This is primarily due to the nascent state of the technology and the fact that many design researchers have yet to become aware of, and address the design challenges in this field.

SOA and Gaps in Multi-scale, Multi-physics Design Knowledge

There are several well-funded and focused efforts aimed at developing nanoscale and microscale design knowledge. Few efforts are targeted at understanding how to simultaneously model and simulate multi-scale, multi-physics design problems. Many efforts have been focused upon improving the understanding of material behavior at smaller-size scales and understanding how this behavior would affect fabrication processes. Two notable areas in which design knowledge was being generated are:

1. Grain size—The Technical University of Eindhoven, where a focused research effort is underway to (a) better understand, model, and experimentally verify the effects of length scales upon the physical properties of materials, and (b) to better understand how this behavior may change with respect to specific design parameters; for instance, quantifying how the coupling of grain size and a part’s minimum feature size affects the performance of structural parts. These relationships are easily plotted so that designers may develop “rules of thumb” and use these rules during the synthesis of concept designs. The experimental and analytic techniques used to produce these rules may also be used to enable rigorous modeling of behavior, thereby providing information that is suitable for concept selection and design optimization. There are complimentary analytic and experimental efforts under way in the Advanced Materials Processing Laboratory at Northwestern University. Specifically, there are efforts aimed at (1) understanding how grain size and material history affect the quality of formed microscale components, (2) creating simulations/design rules that capture the behavior, and (3) linking fundamental physics to process/part design. More efforts of this flavor are required to enable designers to model and design parts with a high degree of certainty.
2. Process design—At the Fraunhofer Institute of Industrial Laser Technology (Aachen) there is a focused effort to understand the fundamental interactions between laser radiation and materials. The aim is to develop the DFX rules and fabrication processes that result in designs with a high probability of success.

This approach enables the design of microscale welded joints in metals and polymers and the fabrication of precision micromolding tools by laser ablation.

The strength of the European efforts in developing design knowledge is due in large part to the strong university-industrial collaborations that take place via mechanisms such as the Fraunhofer Institutes. These mechanisms serve as a “meeting place” wherein scientific knowledge and applied knowledge meet to form a knowledge base that is readily used to design NLBMM parts.

SOA and Gaps in Design Theory and Process

As mentioned before, NLBMM technology is in a nascent stage and most design researchers have yet to discover this field. As such, little work has been done toward developing general theories and approaches that could be used to design NLBMM parts. Efforts in Europe, specifically in Germany, have been driven by university-company collaborations via the Fraunhofer Institutes and similar entities. As such, they are often initially focused upon a specific technology or product. Once the technology or product is proven successful, the knowledge gained during the design and engineering process is extended to create similar products via many low-risk, but economically significant advances. These methods have proven to be successful in developing a large body of DFX rules that may be used to design a number of robust and commercially viable products. General design theory and process work has yet to be addressed. Surprisingly, the use of stochastic methods within the design process was not seen or highlighted during the site visits or at the first U.S. workshop.

DFX and Best Practices

The fabrication processes for a given part must be designed in parallel – that is, concurrently engineered – with the design of corresponding parts. Fortunately, designers may use process-specific metrics (cost of a process, rate of manufacture, and the quality of a part) and design/DFX rules to help generate designs that are compatible with the available fabrication technologies. Investment in research will determine the new rules that will in turn enable designers to select appropriate design-fabrication process combinations.

At the macroscale, designers wish to reduce part count for several reasons: the cost and effort associated with the fabrication of interfaces, the validation of an interface’s alignment geometry, and the overhead associated with interfaces. Compared to lithography-based processes, NLBMM processes are more prone to multi-piece designs that require directed assembly. Although a great deal of past and continuing research is focused upon the directed assembly of small-scale parts—much of it driven by fiber optics and microphotonics—assembly and integration technology needs to be improved. New processes are also needed to produce monolithic parts without lithography-based processes. For instance, processes such as microcasting, microstamping, and microembossing are capable of creating monolithic geometries and more homogeneous systems. These new methods and processes will require new DFX rules.

Standards

Standards for NLBMM parts are currently in a nascent stage and require better definition. Of particular importance are the standards for measurement and evaluation of part characteristics. Without these standards, designers will have difficulty talking with vendors, customers, and others about the specifications that drive the design and fabrication of their parts. These standards should cover geometry, material properties, optical properties, electromagnetic properties, and other related characteristics. Designers need to understand how to design NLBMM parts so that they are compatible with standard measurement methods. The existing techniques for measuring the characteristics of NLBMM parts are far from ideal. Many of these techniques are slow, provide only 2D information, and require destructive evaluation. Clearly, improved measurement tools are needed, as will be explained in a later chapter of this report. A set of rules that govern the design of NLBMM parts “for measurement” does not exist. As a result, most designers use intuition and advice from metrology vendors to design parts that may be measured in a way that does not affect the rate of manufacturing and does not lead to long time constants for manufacturing processes control. Metrology technology is traditionally slow to develop. As such, early designs must be compatible with available technology. “Design for Standard Measurement” will be important to the rapid adoption of NLBMM parts.

Uncertainty and Risk

Uncertainty and risk are unavoidable when designing in the absence of full knowledge. Uncertainty stems from the lack of knowledge required to model performance. The risk that is associated with a particular design may be ascertained if one is able to use models to define a probability of success. In short, it is better to be in a position to ascertain risk than to be in a position of uncertainty. Throughout this assessment, little evidence has been found to suggest that stochastic methods have been employed during the design of NLBMM parts. Given the nascent state of the NLBMM technology, one finds variation in fabrication processes, metrology tools, material properties, and other aspects which must to be considered during the design process. The ability to model these variations and use such models to assess risk is important for two reasons:

1. Knowing the risks may help to prevent the stifling of design concepts in the face of erroneously perceived high risks.
2. A good understanding of risks may be used to guide the distribution of resources toward designs that have a higher probability of success.

At present, the gap between the “existing” and “ideal” in the application of stochastic techniques appears to be a “practice” gap. Designers are not using these techniques, even when the supporting tools/simulators are made available. It is not clear whether new stochastic-based design theories need to be developed for NLBMM design. It is most important then to increase awareness of the benefits of stochastic methods, how they can help in the design of NLBMM parts, and how they should be used during the design process.

Design Concept Architecture

The architecture of a design concept sets limitations on performance, the ease of manufacture, engineering resource requirements, time to market, and the cost of the final product. The ability to generate optimal design concepts and ascertain the best way to integrate meso- and microscale components should be a core competence for a designer. Designers need to understand and apply the concepts of functional decoupling, sensitivity, complexity and signal to noise ratios. There are several general methods that have been developed to guide designers in setting the architecture of parts and systems, for instance Axiomatic design (Suh, 1990, Suh, 2001), six sigma methods (Creveling et al., 2002, Yang and El-Haik, 2003) and robust design (Taguchi and Subir-Chowdhury, 2004). As discussed previously, physics and fabrication fundamentals change at the meso- and microscales. As a result, traditional perspectives and approaches to the generation of architectures must account for this. Recently, efforts have been made to integrate the unique physics and characteristics of the small-scale (e.g., functional) periodicity into the design process (Suh, 2005). More work is needed to better understand how to design concept architectures so that the fundamental issues associated with the physics and fabrication of meso- and microscale components have been addressed.

Given the difficulty of assembling small-scale parts, an important question to consider when constructing a concept’s architecture is: “Should this product be designed as a heterogeneous or homogeneous system?” At present, the most appropriate use of the fundamental approaches that dominate macroscale designs (heterogeneous architectures and packaging), VLSI designs (homogeneous), or a mix of the two is not always readily apparent. Given the link between product architecture, cost, engineering resources, and time to market, additional research in product architecture for small-scale and multi-scale applications is in order.

The SOA and Gaps in Modeling and Simulation Tools

The SOA in modeling and simulation relies primarily upon the use of legacy tools that are based upon macroscale physics and continuum-based modeling. Several commercially available tools are capable of simultaneously modeling multiple physical phenomena within the limits of continuum models (COMSOL, 2005, ANSYS, 2005, COSMOSM, 2005, ALGOR, 2005, NEiNASTRAN, 2005, MSC Software, 2005, ABAQUS, Inc., 2005, CFDRC, 2005, MEMSCAP, 2005, IntelliSense, 2005). However, these tools often fail to provide accurate results when the type or nature (continuum or non-continuum) of the dominant physical phenomena changes. Four approaches are currently used in practice:

1. Designers use experimentation to develop empirical models of phenomena and experience.
2. Designers apply correction factors to map erroneous, continuum-based simulation results onto experimental results.
3. Designers use the appropriate physics to generate custom computer-based modeling and simulation tools.
4. Designers collaborate with established software vendors to develop custom modeling and simulation tools.

The panel observed the latter approach several times during site visits in Europe. The overall impression is that the European designers were focused upon generating accurate and robust modeling tools. The most successful designers were observed to have utilized a hybrid approach in which designers augmented existing software to meet their needs. This indicates a technology gap that is probably best addressed by software vendors. It would be very useful to have more open source modeling and simulation tools. At the very least, customers should be willing to more readily adapt them to accurately model custom applications. The open source approach to multi-scale modeling exists to some extent in tools such as FEMLAB (COMSOL, 2005), though a fair amount of expertise in programming is required to take advantage of this. Designers should look for the capability to customize commercial modeling tools when they are seeking to purchase modeling and simulation tools for NLBMM part design.

Integration and Fabrication Design Tools

Given the challenges associated with the selection of concept architecture, the fundamentally different nature of NLBMM micromanufacturing processes, and the lack of trained human resources, integration and fabrication issues will likely dominate initial design and engineering efforts. At present, designers often develop their own means of modeling and simulation via experiment, or via a combination of extensive experimentation and custom-designed simulation tools. Clearly, this is not the most cost-, effort-, or time-efficient means of ensuring that products will be well-suited for fabrication and integration. Researchers should be encouraged to generate modeling and simulation tools that reduce the cost and time associated with extensive experimentation.

Stochastic Design Tools

There is a need for modeling and simulation tools that link the performance of components to variations in the characteristics of the part and the variations in the performance of a system to variations in the performance of its parts. In many cases, the preceding may be addressed by custom-made, stand-alone simulations (e.g., Monte Carlo simulations). Unfortunately, many of these tools are difficult to learn and they are not integrated with existing geometric and behavioral modeling tools. This is perhaps the reason that stochastic design tools are not widely used in engineering design. Other modeling tools, for instance computational fluid dynamics (CFD) and finite element analysis (FEA)—both of which are integrated into computer-aided design (CAD) programs—find widespread use in engineering design. Computer-aided application software (CAX) vendors should consider adding this functionality to their programs and designers should look for this functionality when purchasing CAX tools.

Multi-physics, Multi-scale Design Tools

Behavioral modeling—Designers require tools that are capable of multi-scale, multi-physics behavioral modeling. Such modeling includes simulation of part function, assembly function, and the simulation of fabrication processes that are to be used to make the parts. Several commercial simulation packages (COMSOL, 2005, ANSYS, 2005, COSMOSM, 2005, ALGOR, 2005, NEiNASTRAN, 2005, MSC Software, 2005, ABAQUS, Inc., 2005, CFDRC, 2005, MEMSCAP, 2005, IntelliSense, 2005) are capable of multi-physics modeling at the macro-, meso-, and microscales. The development of a theoretical basis for multi-scale design tools is in the early stages. A few annual conferences have been seeded and journals have been started (Multi-scale Modeling and Simulation, <http://epubs.siam.org/sam-bin/dbq/toclist/MMS>, International

Journal for Multi-scale Computational Engineering, <http://www.edata-center.com>) to disseminate news of early advances. To date, the theories are application-specific, and are both derived for and applied in fields other than manufacturing. A micromanufacturing focused effort in multi-scale, multi-physics modeling tools is needed.

Geometric modeling—Commercial CAD tools are readily used to model the geometry of small-scale parts. Although these tools may be used to “get parts made,” their utility and impact would benefit from specialization for small-scale design. This would be particularly useful when new DFX rules are required to restrict modeled geometries to be compatible with available fabrication processes. For instance, geometric modeling programs for MEMS automatically generate mask patterns and provide both guidance and constraint for DFX (MEMSCAP, 2005, IntelliSense, 2005). The same capabilities would be helpful when NLBMM parts are fabricated using non-traditional processes.

Tools for Modeling Economic, Environmental, and Other Impacts

The potential impact of NLBMM technology is difficult to ascertain without appropriate modeling tools. For instance, the economic and environmental impacts of this technology have the potential to be large. The economic impact is described in a preceding section. The environmental impact is potentially significant due to the reduction in energy costs, pollution, and the material waste associated with smaller-scale parts and the smaller machines that make them. Given the perceived risks associated with new technologies, it will be important to have tools that model the impact and thereby help to justify the need for NLBMM products.

Gaps in the Processes Used to Develop Human Resources

Synthesis is a process in which knowledge, skill, and experience are used to guide a process wherein several concepts are created and then refined to create practical designs. Different perspectives exist on what synthesis, precisely, is. At one end of the spectrum, synthesis is considered to be a process by which existing knowledge, design rules, and concepts are combined to derive new concepts. In another approach, synthesis is the development of new concepts by generating new design rules; this is often called invention. In yet another view, synthesis is the result of mathematical models that are manipulated to provide alternative designs.

The importance of these different perspectives for our discussion will be explained shortly. For now, the key point here is that synthesis is in part dependent upon a designer’s perceptions and experience. Although computer-based programs have shown great promise in performing synthesis via the first and third methods described above, they must be “fed” rules and they are therefore not yet capable of competing with designers in the second method. Two important observations come from this: designers are needed to codify the rules and designers are needed to generate new rules. An important problem for the design of NLBMM parts is that most designers are “preloaded” with intuition that enables them to understand and make design rules for macroscale applications; however, macroscale intuition is not always applicable at the meso- or microscale. Without meso- and microscale experience, designers will not be able to assess and mitigate the risks associated with designs. As such, meso- and microscale design education is needed for those who will practice synthesis in this field or for those who design synthesis tools for use in this field. Knowledge development must be facilitated in three ways:

1. *Existing knowledge and logic*: Undergraduate, graduate and professional courses are needed to help disseminate knowledge of the dominant physics for meso- and microscale parts. MEMS/VLSI-specific fundamentals (Campbell, 2001) are commonly taught in MEMS manufacturing courses (Madou, 2002). The existing materials do not fully cover the required knowledge and design rules in sufficient depth for NLBMM design. As a result, either complimentary or new materials must be developed to disseminate this knowledge.
2. *Experience and skill*: Designers must obtain experience in synthesizing, modeling, fabricating, integrating and implementing meso- and microscale parts and systems. The means for designers to gain experience and skill should be integrated into the classroom, research projects and internships. In many cases, the resources required to do this (e.g., fabrication, testing, etc.) are expensive. Therefore, the

combination of measurement tools, computer simulations and haptics (Ferreira et al., 2001), may be cost-effective “hands-on” experiences.

3. *New knowledge*: As NLBMM design and manufacturing are nascent fields, the broad and rapid advance of these technologies will best be served by a first generation of designers who are capable of generating knowledge to fill the gaps between existing and required design technology. This talent pool must be developed via training programs in basic and applied research.

Other topics that are important to add to education are;

- i. Simulation and experimental methods
- ii. Handling risk and uncertainty
- iii. System architecture/design

SUMMARY AND CONCLUSIONS

The design of/for NLBMM parts is unique due to: (1) the ability of the meso- and microscales to serve as a “handshake” between the macro- and nanoscales, (2) the transition in dominant physics that often takes place over the meso- and microscales, and (3) the change in the fundamental nature of fabrication processes that occurs over the meso- and microscales. These unique qualities give rise to gaps in the knowledge that supports the design of NLBMM parts, the design theory and process that are used to specify the embodiment of a design, and the design modeling and simulation tools that provide information for design decisions. Design researchers and practitioners have not had adequate time to solve the nascent and unique challenges that are associated with design of/for NLBMM technology. Continued research is required, with particular emphasis on encouraging work that helps to streamline the process of transforming knowledge into designs.

Another important issue for the design of NLBMM parts is that most designers are “preloaded” with intuition that enables them to understand and make design rules for macroscale parts and manufacturing processes. As such, meso- and microscale design education (beyond that available in VLSI/MEMS education) is needed for those who will practice design in this field. Design of NLBMM parts will require a new design perspective in which the behavioral dependence upon geometry/time scales is inherent to the design process. Designers therefore require tools that are capable of multi-scale, multi-physics behavioral modeling. This includes simulation of part function, assembly function, and the simulation of fabrication processes that are to be used to manufacture the parts. Existing geometric modeling tools, such as CAD, are sufficient to “get parts made,” though their utility and impact would benefit from modular specialization for small-scale design. For instance, modules or “plug-ins” work within the CAD tool to provide feedback on the manufacturability of a given geometry. This will be particularly useful when DFX rules are substantially different from those that are used at the macroscale. This leads us to the need for new DFX rules and guidelines that will help designers select appropriate design-fabrication process choices, and the means to codify the rules so that they may be incorporated into behavioral/geometric modeling tools.

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