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Reliability Shortcomings for Micro Nano Technology-Based Systems

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ABSTRACT

Micro Nano Technology-Based Systems (MNT-Based Systems) are expected to provide unprecedented capabilities for aerospace applications. However we have not sufficiently addressed the reliability of such systems for a number of reasons. For example, our foundational understanding of such systems is incomplete at the basic physics level and our understanding of how individual subsystems interact is much less than we originally assumed. In addition the manner in which we operate during the product realization cycle has large implications for the ultimate reliability we can expect to achieve. Currently it is quite difficult to determine the reliability of MNT-Based Systems and is in fact borne out by a number of estimates we have seen that are unsatisfactory. We shall discuss a number of issues that at present have slowed our progress in developing NMT-Based Systems and have deterred us from effectively ascertaining the true "reliability" of such systems.

Keywords: Microsystems, Reliability, Design, Product Engineering, Modeling and Simulation

1. INTRODUCTION

Many microsystem-based products are in the marketplace today and enjoy a reasonable level of success. That success has provided the motivation for many individuals to enter into the field in search of great rewards. However, the story is one of some successes and many failures substantiated by the failure of many startup companies over the last ten years. Central to that is whether a product can be offered at a performance level and price the market will embrace. Applications in the automotive field, the medical field, and in displays [1] come to mind where there is a demand for a large number of devices that provide high performance relative to their costs. Apparently the reliability of these systems is quite high and we can only surmise that a substantial amount of resources went into establishing their inherent reliability as part of the performance equation.

However, our own experience with microsystem development has been mixed. Maybe akin to that experienced by many of our colleagues in their less-than-successful ventures. What we consistently encounter is a lack of information at each step in the development process. Much of this has to be attributed to the general immaturity of the underlying technologies, where in may cases we are attempting to develop microsystems using processes and methods that are not well understood. Adding to that mix is the reality that we consistently are operating with limited resources on a schedule that allows little room to deepen our understanding of the underlying physics. The norm seems to be we proceed with insufficient information to carry out a development.

In many cases a typical product development cycle is started with a schedule that is too tight and with inadequate resources and staff. In addition, the requirements are generally poorly understood or ambiguous, and the true operating environments are unknown. This combination added to a myriad of uncertainties in processing, material behavior and a general lack of knowledge of the underlying physics is a true recipe for failure. Reliability considerations haven't even entered into the mix at this point. In fact reliability is often an afterthought in a product development program due to the staggering obstacles faced in just building a functioning device in the face of the many unknowns described.

2. MICROSYSTEM EXAMPLES

We describe a number of typical examples of work we have carried out in the past where our understanding of the underlying behavior was incomplete prior to and during the design and fabrication process. In each of these cases modeling was carried out as part of the design process however, the modeling that was used was not adequate since a number of other important factors were not included in the models used.

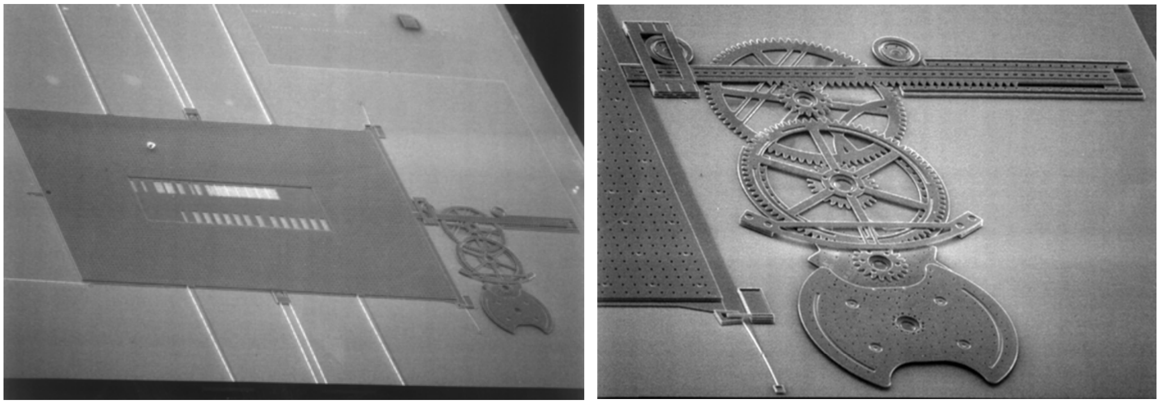

Figure 1 SMM Acceleration Sensor.

Escapement Mechanism Example

A surface micromachined (SMM) acceleration sensor is depicted in Figure 1. The device consists of an inertial mass suspended by flexures. The application requires the sensor to differentiate between an impact and a sustained minimum acceleration. The requirement is satisfied by the incorporation of a mechanical damping mechanism. The mechanism utilizes a gear train terminated with a verge escapement (a mechanism commonly used in ordinance applications where energy is dissipated by momentum transfer during impact). A rigid-body dynamic model was used to evaluate the gear train design. The gears are constrained by revolute joints with 0.5 micron gaps between the joints and the rotating gears. Testing post fabrication revealed substantial friction loss in the joints that resulted in inefficient operation. These results were inconsistent with the modeling. This gearing design had been used in other applications where increased torque is obtained from input to output. In this application, the torque is reduced between input and output and angular velocity is increased. To realize this mechanism a new revolute joint design was required. In this case the modeling was inadequate and as a result the first iteration of the design did not function appropriately. Our understanding at the time of the friction and other mechanical energy dissipation effects was insufficient and the design did not function as anticipated. An understanding of the underlying physics for this system is a must and as a result, more resources were required to develop the device.

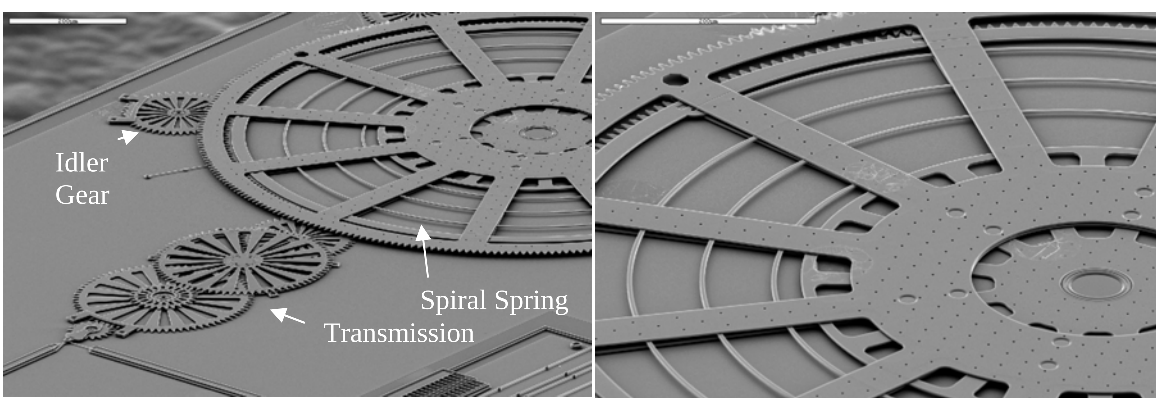

Figure 2 SMM Mechanical Timer

Spiral Spring Example

The design of a surface micromachined mechanical timer [2] is depicted in Figure 2. The mechanism utilizes a spiral "hair" spring to store potential energy. The ends of the spring are attached to separate gears nested on top of one another that rotate on two independent revolute joints. To wind the spring, the upper gear is held with a mechanical latch while the lower gear is rotated using a rotary actuator. Post fabrication, a stiction issue was encountered between the spring and the substrate which precluded operation. Modeling results failed to predict this condition. Design modifications were later implemented to resolve the problem. Our understanding again of the underlying physics was inadequate. The actual friction and Stiction effects in this system were estimated from previous experience however for this combination of design and processing we underestimated these effects. As a result, the development required more resources to correct the problem. While the problem was corrected, our understanding of the long-term effects on this system is incomplete. Additional fundamental work is required to assess wear, fatigue and lifetime performance.

Packaging Example

A MOEMS (Micro Opto Electro Mechanical System) is depicted in Figure 3. The system consists of a VCSEL (Vertical cavity Surface Emitting Laser) array mounted beneath a MEMS sensor with a GaAs photo detector array mounted on the MEMS top surface. An ASIC is mounted within the package and is used to interpret electrical information signals sent from the photo detector array. The MEMS device is coated with a SAMs (Self Assembled Monolayer) coating to reduce stiction. During normal handling, the attachment sights affixing the photo detector array broke free from the MEMS surface. Failure analysis revealed an adhesion problem with the epoxy used for bonding. Flip-chip, bump-bonding techniques developed later were used to resolve this problem, but at a cost to the project schedule. Early packaging synthesis failed to identify this issue and resulted in a schedule loss. Again early modeling efforts were incomplete and failed to predict the problem.

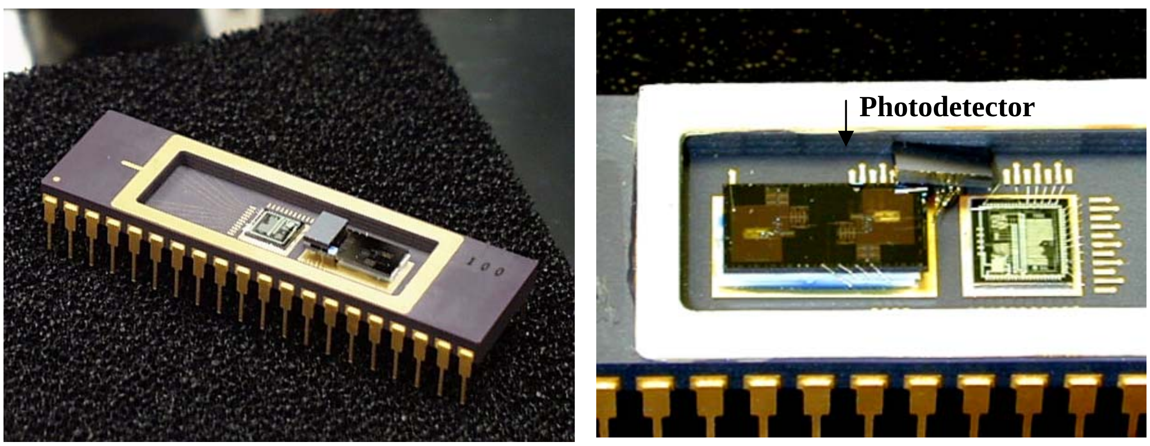

Figure 3 MOEMS Packaged in a 32 pin DIP

Buckling and Impact Example

A bulk micromachined acceleration switch is depicted in Figures 4, 5 and 6 below. The sensor is fabricated on an SOI wafer using DRIE processing. Flexures patterned on the front side of the wafer are used to suspend an inertial mass that is patterned with gold. The backside of the wafer is DRIE (Deep Reactive Ion Etched) processed to separate the inertial mass from the substrate and to separate each die from the wafer. Initially the design utilized a set of folded flexures. Post fabrication, acceleration testing revealed a buckling issue within the flexures that resulted in a bistable state. Later modeling confirmed the test results. To remedy the issue, a new flexure design was synthesized to stiffen the spring constant value in the radial direction while maintaining the required softer value for the longitudinal direction. The new design also required the incorporation of mechanical stops to preclude overloading of the flexures radially. Subsequent testing of the new design revealed a processing and a design problem. Lateral under etching during DRIE processing created substantial particle generation during release and operation. Also, a thin layer of silicon attached to the frame was damaged during radial impacts between the inertial mass and the substrate sidewall. Broken shards of silicon migrated to the device's electrical contacts and resulted in electrical contact failure. Changes to the design and processing later resolved some of these issues but the difficult job of assessing reliability remained. Our inability to model the DRIE process adequately contributed to our difficulties. An understanding of the etching process would have allowed us to predict the issue prior to fabrication. Again additional resources were required to alleviate the problem.

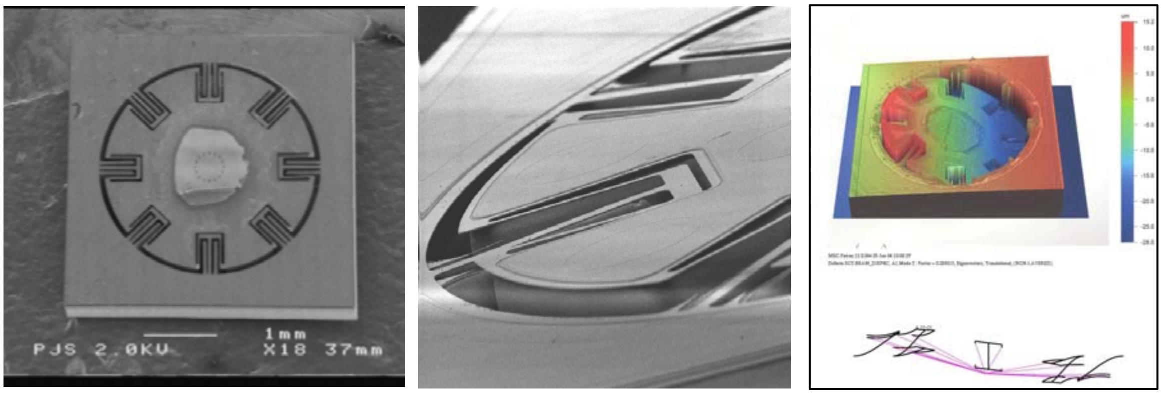

Figure 4 Bulk Micromachined Acceleration Switch with Folded-Beam Flexures

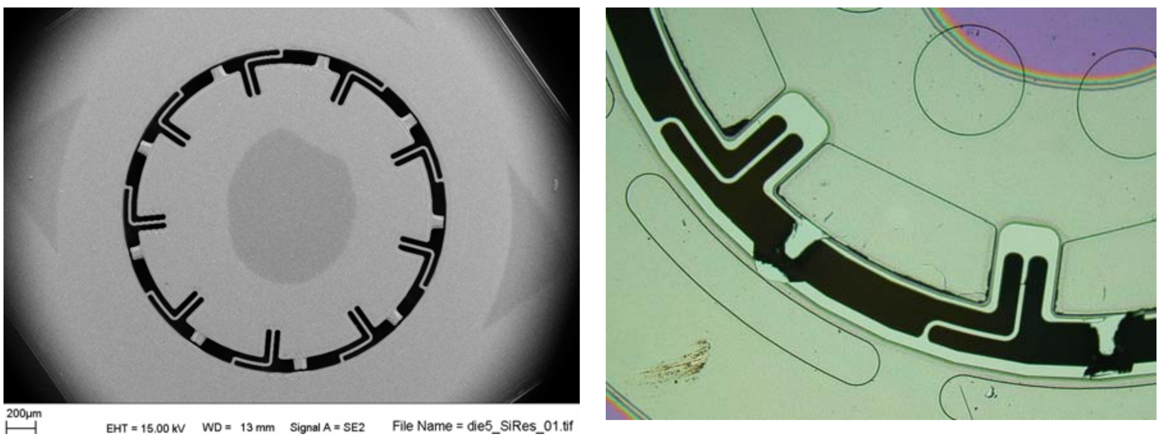

Figure 5 Bulk Micromachined Acceleration Switch with Modified Flexures

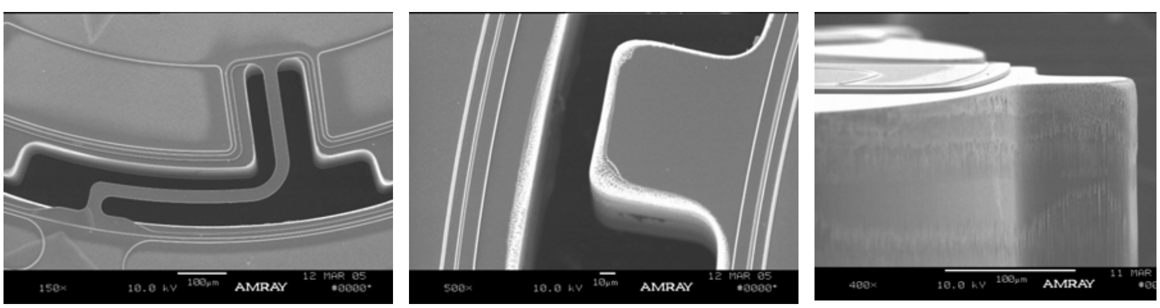

Figure 6 Bulk Micromachined Acceleration Switch Post Process Improvements

Stiction Issue Example

Three surface micromachined latching micromirrors [3] are depicted in Figure 7. Mirror sizes are 100 x 150 microns. The spacing between the mirrors is one micron. The application required a 2000 x 2000 mirror array with independent addressing. An electrostatic actuation scheme is used to independently tilt each mirror pixel ten degrees. Beneath the surface of each mirror is a separate electro statically driven mechanical latch used to hold each mirror in the tilted state during unpowered operation. A third actuation mechanism is used to pull the non-tilted mirrors flat against the substrate during imaging. Packaging of the final assembly requires massive interconnections for each independent electrical line.

During testing, an electrical charging problem was encountered. Trapped charge within the actuation electrodes limited operation. Subsequent electrical grounding improvements were incorporated to resolve the problem. The complexity of the design made it difficult to create a complete system model where charging and stiction effects were accurately represented. Such a capability would have allowed us to circumvent the problem the first time.

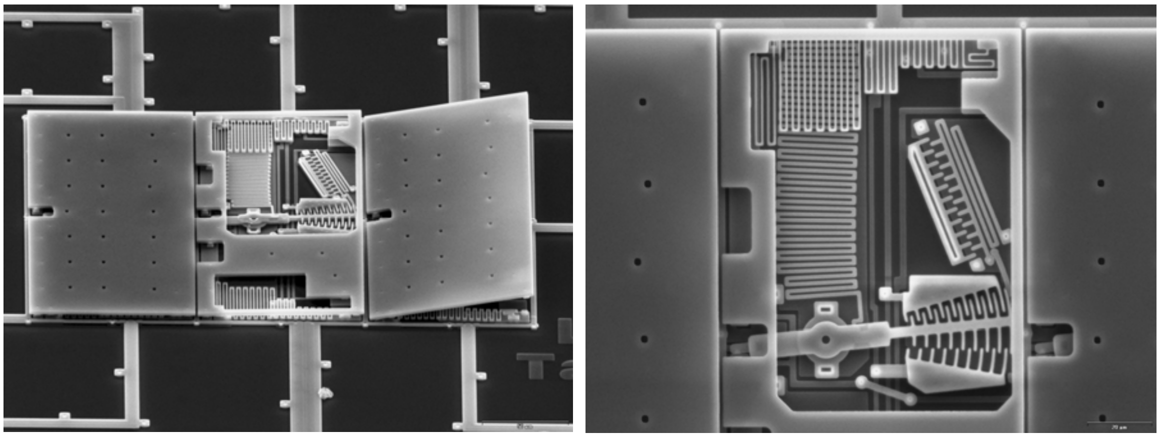

Figure 7 SMM Micromirrors

Packaging Issues

MEMS packaging is widely known to be challenging. Three examples of packaging issues are depicted in Figure 8 below where devices were fabricated using surface micromachining (SMM). Particles migrating from broken silicon and a dirty packaging environment rendered the first device inoperable. The second image reveals substrate damage that occurred during die placement within a custom package. Finally the third picture depicts degradation within a SAMs coating used for stiction reduction as a result of an elevated epoxy curing temperature that exceeded the critical thermal limit for the SAMs coating. These and many more packaging issues are commonly missed during early modeling and design synthesis and result in project delays, cost increases and performance degradations.

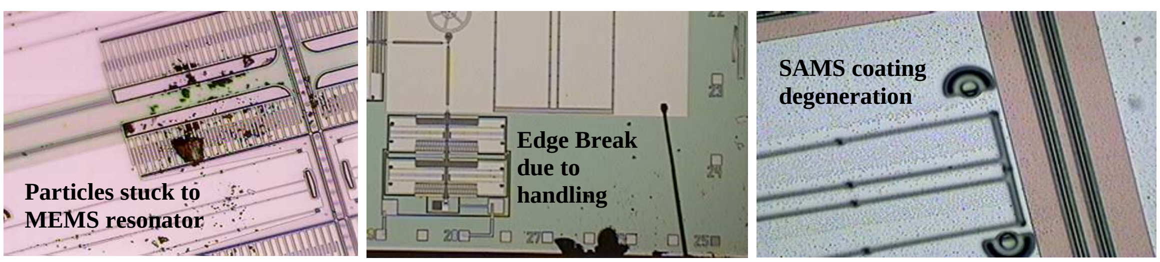

Figure 8 SMM Packaging Issue

Wear Example

The affects of environmental conditions on MNT-based systems is difficult to predict. Figure 9 below shows two completely different outcomes for two identical surface micromachined actuators [4, 5]. Each actuator was driven over 600,000 revolutions in two different humidity environments. Tremendous wear which eventually resulted in complete device failure was encountered for the actuator operated in a very dry environment. These results were not predicted by prior modeling.

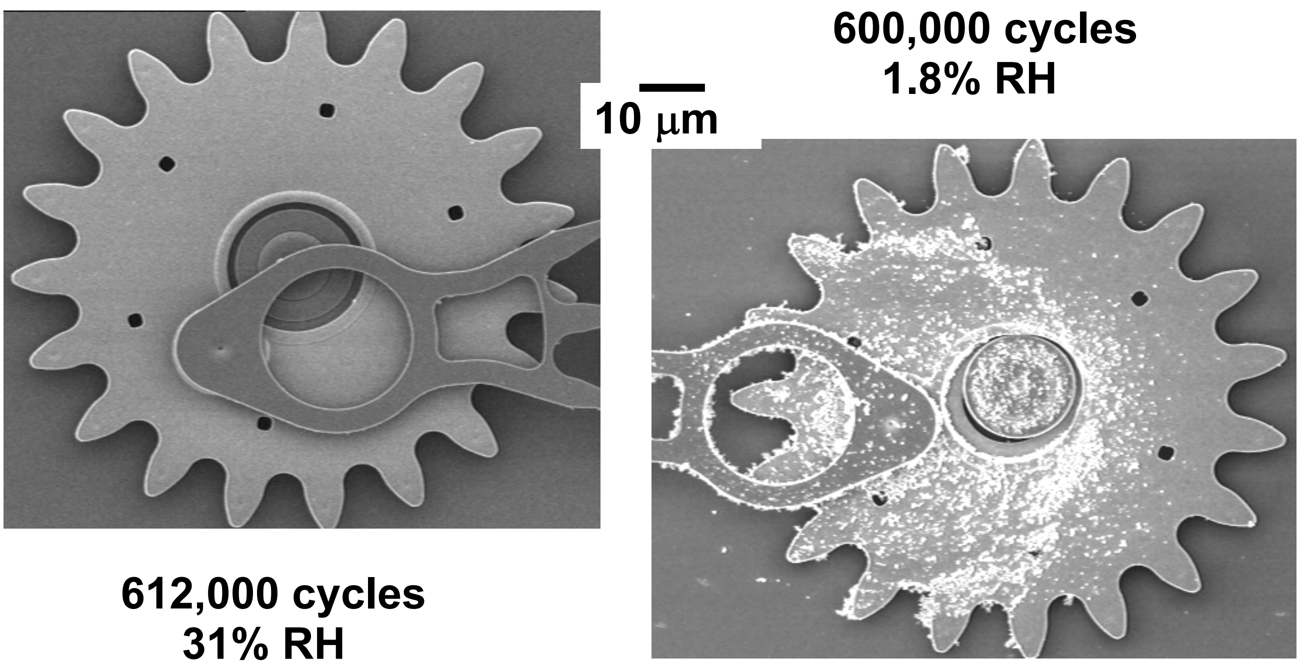

Figure 9 SMM Rotary Actuator Post Environmental Testing

These examples illustrate the difficulties we encounter as the norm when developing microsystem-based components. From these examples we can infer that a profound understanding of the system physics is certainly a first step in our journey towards developing a means for predictive reliability.

3. IMPEDIMENTS

What are the impediments to determining the reliability of a microsystem-based product? First the goal of a product development is to ascertain the reliability of such a product before thousands or millions are produced at significant cost. A fundamental understanding of the underlying technology is the first step towards assessing product reliability. However this is exactly what we lack; a fundamental understanding. How do we arrive at this required understanding? Part of the answer is obvious; a deliberate investment of resources must be made to generate sufficient information in the form of understanding the underlying physics. The second part which we will discuss further in a subsequent section is: What is the method or process we use to estimate or assess reliability? The answer here is at present there is not a satisfactory method for assessing the reliability of systems well before they are fabricated and tested. Reliability data at present is derived from in-product use and from laboratory testing.

The perceived current state of MNT reliability is that it is virtually nonexistent, except for those cases where a large amount of product field experience has been obtained. There are some excellent individual reliability investigations that have been carried out in the past both here at Sandia and elsewhere, see for example [4, 5, and 6]; however, it is difficult in those cases to extract the necessary information needed for a specific product development. In reality the field of microsystem reliability is disjointed and uncoordinated. There are some efforts as part of some CANEUS (Canada-Europe-USA-Asia organization for the advancement of MNT for aerospace applications) activities to coordinate the reliability efforts of a number of groups in Europe, the Americas and Asia. This effort is only beginning but is an excellent step in bringing the field together as it applies to MNT. Due to the relative immaturity of MNT there is some belief that this immaturity makes it extremely difficult, if not overwhelming, to assess reliability given that it remains a difficult problem to predict with more well-developed and understood technologies.

To date minimal resources have been invested in the field of micro and nano technology-related reliability. While there are many researchers in the MNT field as a whole, there are very few involved with developing assessment methods and discovering underlying physics useful to reliability assessments. Given that MNT is an inherently multidisciplinary field exhibiting complex physics, it seems that one way to tackle the difficult problem would be to organize into groups that could effectively divide and conquer this immense problem. MNT reliability presents us with an opportunity for the science and engineering community to organize a concerted effort to establish the foundations of MNT reliability through a synergistic and cooperative endeavor amongst a variety of institutions at an international level.

4. SCIENCE-BASED ENGINEERING RELIABILITY

At present we live in the empirical world; especially when it comes to reliability determinations. Currently the only successful method available to determine reliability is through experiment. As mentioned earlier, for those products that have been produced by the thousands or millions there is an opportunity to assess their reliability. However for those products that are either fabricated in small quantities or are still in the design stage it is extremely difficult to estimate their reliability without previous experimental or functional experience with a statistically significant number of products.

The difficulty that arises is reliability determinations based on experimentation are quickly becoming obsolete and cost prohibitive. The reason being as systems become more complex, it is nearly impossible to experimentally determine the myriad of subsystem interactions and permutations that occur within a system. The number of required tests is overwhelming and therefore almost impossible to carry out. We plainly are unable to economically determine reliability for many present day systems under development.

The interesting question that arises is could we determine the reliability of a MNT-based system prior to its fabrication and subsequent use? The fact is we're not even able to do that with "conventional" systems today. Our approach to determining the performance and reliability of MNT-based systems must change. Empirically-determined performance and reliability cannot be the cornerstone technique used for developing MNT-based systems, or any other type of system for that matter, due to their evolving complexity. We clearly are at a crossroads; our advancements are not progressing as quickly as envisioned. Predictions from 20 years ago of what our capabilities in microsystems would be today are far above what we have actually achieved. There have been great advances made by a number of groups; however, we have not converted that research into ubiquitous product.

The idea behind science-based engineering reliability is to discover and understand, in a profound manner, the underlying physics that forms the foundations of an MNT-based product or system and create a predictive capability validated by physical testing. Conceptually, if we assemble the system physics and use this to create a predictive capability we can determine performance and reliability before fabricating such a system. A predictive capability such as this would allow us to optimize the design of complex systems, determine their responses to a variety of environments and ultimately predict the reliability of such systems with virtually no testing. Such a modeling and simulation capability would require high performance computational capabilities of a magnitude not previously available. However today we are approaching the required computational capabilities needed for this important task.

To solve this problem we need to take a systems engineering approach to managing the numerous inputs that would be required to assemble a predictive reliability tool. The idea would be to partition the problem into sub-elements or subsystems and discover, uncover and extract the underlying subsystem physics from analytical and experimental investigations of each corresponding sub-element. Each sub-element would be a fundamental entity that could exhibit multi-physical behaviors. The central idea would be to determine what the physics of a sub-element is to a fidelity that is useful for its later incorporation into progressively more complex subsystems. A validated predictive model would be developed for each sub-element. The more complex subsystems would incorporate the validated predictive models from the fundamental sub-elements into a predictive model that would account for the sub-element interactions within the more complex subsystem.

A system response function would be developed by incorporating the complex subsystem predictive models into a model that also takes account of the subsystem interactions as part of the system configuration (Figure 10). This system response function would be capable of predicting system performance under all conditions of environments. Such a capability would permit the optimization of a system under specified constraints and yield performance and reliability estimates for the system.

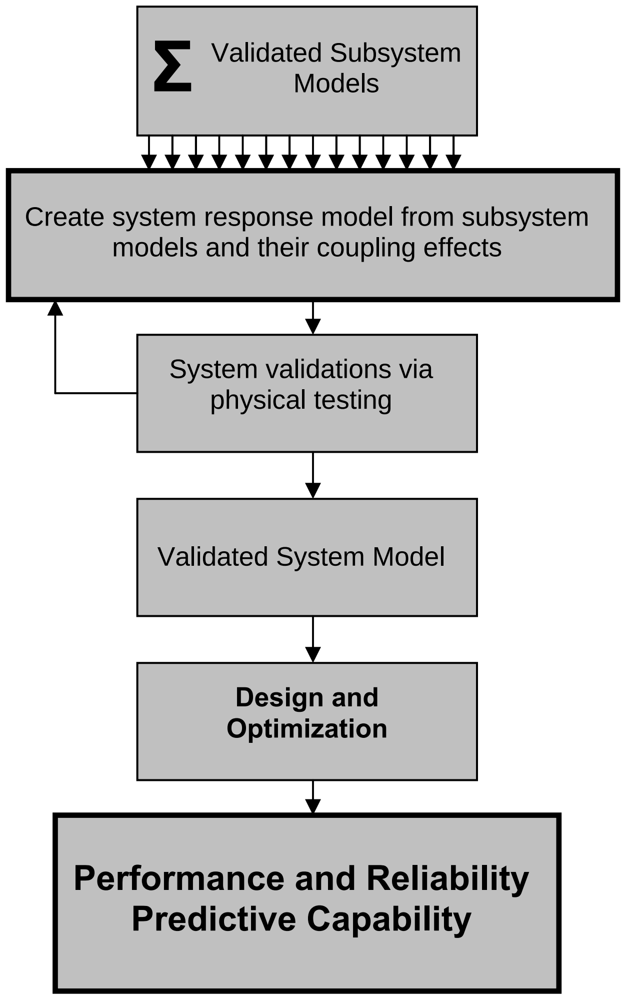

Figure 10 System Model Development

The essence of this approach is to study sub-element and subsystem behavior, develop a predictive capability based on the discovered sub-element physics and use the individual subsystem predictive capability to construct a total system predictive model. This capability can then be used to optimize designs, predict their behavior under many conditions and extract information pertaining to system reliability responses under the environmental conditions imposed. Such a tool at present does not exist due to the inherent difficulty of the problem. However, this is a tractable problem within our current state of scientific knowledge and technical capability.

Nearly every stage of the research, development and product engineering cycle has an important effect on system reliability. The following are some of the issues that will require consideration when developing a system performance and reliability predictive capability:

1. The design of the device or system.
2. The product realization process.
3. The nature of the underlying physics.
4. Misunderstanding of the underlying physics.
5. Materials used play a central role.
6. Environmental effects.
7. Lack of understanding of requirements.

8. Processes used during actual production.
9. Lack of understanding of complex subsystem interactions.
10. Inadequate modeling and simulation tools.

These and a whole host of other effects are major contributors to the reliability behavior of a designed system. What steps must be taken to solve this problem?

5. RELIABILITY INFRASTRUCTURE

What we have generally lacked is a strategy and plan for solving this enormous problem. It is clear that we must organize a number of partner institutions at an international level to form a group that utilizes the strengths and resources of various collaborating organizations. Through a concerted, coordinated effort we can effectively partition the problem into a number of connected investigations to establish the scientific foundations required to develop a science-based engineering reliability capability. The formation of a consortium to tackle a problem of this magnitude will permit each institution to greatly leverage their individual work and resources.

To establish an MNT reliability infrastructure we must ask what are the basic elements of a reliability infrastructure? The following list examines some aspects for an infrastructure.

1. Who would be the members of an MNT Reliability Consortium?
2. What is the output or deliverable?
3. How would this activity be funded?
4. What are the intellectual property issues?
5. Is there an appropriate existing organization that could lead such an effort?
6. How could we set up an organization to coordinate the activities?
7. Where would we access the computational capability required?

6. CONCLUSION

We are generally in agreement that the existing state of the art is insufficient to provide a reliability assessment of a system prior to its fabrication and testing. The basis for reliability at present is based on empirically derived data. The use of fundamental sub-element physics has not been utilized to derive reliability models for systems. The evolution of systems is now at a point where it is virtually impossible to economically test such systems thoroughly to yield a reliability assessment.

The opportunity exists for a science-based engineering reliability methodology to lead us to the development of a predictive capability for MNT-based systems that would yield performance and reliability assessments well before such systems are ever fabricated. This opportunity is what we propose to take advantage of by coordinating our efforts in the field to synergistically solve this problem.

We propose the formation of a multi-partner Science-Based Engineering Reliability Consortium to organize, plan and coordinate efforts to unravel the largely unsolved problem of MNT-based system reliability. We would be eager to host a meeting at our laboratory or help organize such a meeting at an appropriate conference to begin the steps necessary to form a Science-Based Engineering Reliability Consortium.

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