Innovative Multifunctional Concepts Enabled by Novel Fabrication Strategies

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ABSTRACT

Often design, materials and fabrication development are pursued as successive steps in a technology implementation cycle. This stymies a concurrent thinking approach that would allow an integrated strategy where various stages of the technology development life cycle are concurrently considered. This is particularly true for multifunctional systems where new architectures must be considered within the constraints of design, materials and manufacturing.

We propose a new strategy in multi-functionality by incorporating electro-magnetics and sensor components directly on large passive load bearing structural surfaces without structural or profile debits. This approach based on ***mesoscale multilayer surface engineering*** *has recently been enabled through the development of conformal, low temperature direct write technologies for both patterning and 2 ½ D engineering of multilayer circuit architectures. The advantage of this approach is that the structure itself is not compromised while and the available passive regions are utilized. Furthermore the developed approaches can be incorporated into various substrate materials (metals and composites) and thus can be transitioned to both new and legacy DoD platforms.*

This paper discusses the proposed methodology for multifunctional material integration using ***layered and through-thickness-controlled*** *device architecture and compositions. This will provide surface-engineered systems with appropriate embedded interconnect and wiring strategies. Initial examples of concepts for integration of structural capacitors and sensors will be discussed.*

1.0 INTRODUCTION

1.1 Multifunctional Systems: Need/Opportunity

Modern aerospace and military systems are continually driven to be *lighter and smarter*: they require ever decreasing weight margins, yet must incorporate wide ranging electronics and sensors. Furthermore the

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addition of these devices also sets-up unprecedented electrical power demands to meet the multitude of electromagnetic and sensor functionalities. Thus, it is well recognized that next-generation military systems will need to be multi-functional, i.e., they will need to provide several engineering functions *concurrently*, such as structure, sensing, electromagnetics, thermal management, and power generation/storage from the same structure. Research in each of these areas is underway; however, to date, these efforts have not been highly integrated. This is partly due to the need to bring multidisciplinary expertise to meet wide ranging design, materials and manufacturing requirements. In addition, the design philosophy itself needs to be re-examined based on new strategies and concepts. New manufacturing technologies, hitherto not-envisioned, have to be brought to bear to meet the integration goals. Finally, the implementation of multifunctional systems will require a synergistic, holistic approach to develop technologies in a systematic way.

What are the critical requirements to achieve this?

Several key attributes can be identified. Such a technology should provide:

- *Combined* design approach to energy harvesting/storage, structural optimization, functional devices, wiring and thermal management.
- *Flexibility* to integrate different design/materials technologies with process methodology.
- Design tools that not only address structural optimization but presented within the context of available device, material and innovative fabrication methodologies.
- Robust model- and experiment-derived *design criteria* for optimized function, structure design and efficiency.
- Scalable manufacturing methodologies for cost effective implementation.

Equally important is the ability to assess which platforms would most benefit from an integrated multi-functional system, as the overhead of implementing such a system is considerable. Finally, issues such as portability, weight, field repair, and dependability must be adequately addressed.

1.2 Approaches to Multifunctional Systems

This recognition of need has led to various research activities in this area, principally under the sponsorship of department of defense in the united states. The proposed NATO workshop will clearly highlight the various activities, but a brief classification is provided here to differentiate the activities of this work and to put it in context of the overall strategy.

- DARPA's Synthetic Multifunctional Materials program seeks innovate new materials concepts that will perform multiplicity (at the very least duality) in function. A number of efforts are underway in the arena of structure + power, structure + armor, structure + electromagnetics etc. One goal of this program is to envision multifunctionality as inspired through a variety of natural systems which in many cases demonstrates multifunctionality. Such concepts if successful can be revolutionary in design and applicability. [1]
- Other DoD efforts such as at the Air Force Research Laboratory (AFRL) focus on integration strategies aimed at meeting multifunctional goals [2]. Fiber reinforced composites offer an interesting platform here as they offer means to incorporate functional fibers in a periodic array that can perform a new function while meeting the structural requirement. This will also allow integration of multi-functionality to new composite based systems that are under consideration.

The above efforts are clearly promising and offer potential solutions for future integration into multifunctional systems. As is the case in many new technologies, a number of challenges have be overcome including meeting structure reliability/performance attributes, functionality of the device itself, and finally ease of integration, manufacturability and cost effectiveness.

1.3 Proposed New Strategy: Enabled by Unique, New Fabrication Technologies

We herein envision a new concept of a *mesoscale surface-engineering* (MSE) as means to build and integrate layered and discrete functional devices that will enable 2 ½ D integration of sensing, electromagnetics, power harvesting and storage through sequentially and spatially controlled layered structures. The advantage here is that the **structure itself is not compromised while available surface and volume regions are utilized**. The key goal is to add multifunctionality without structural debits and ease of implementation.

For instance, conventional aero-structures can be deemed to be principally passive, i.e., they have large areas that carry loads and perform aerodynamic functions but the surface space itself is essentially unused.

What if it were possible to utilize the structure in a multifunctional manner? For example,

- use the large exposed surface for electromagnetic functions (communications/imaging)
- utilize the large open surfaces for solar or power scavenging and power storage applications
- integrate sensor arrays for situational awareness including environmental and structural monitoring
- incorporate wiring, logic and computational functions locally, enabling autonomous responses to stimuli
- Provide means to connect the information towards decision making either locally or remotely.

The proposed concept as envisioned is shown schematically in Figure 1. The idea is to use the multi-layer surface engineering concurrently with direct-write based patterning technologies in a synergistic manner to develop a radically new approach to integrating sensors, electronics (e.g. antennas, structural capacitors), interconnects (wires), and information transfer components (both wired and wireless) enabling a paradigm shift in how the surfaces of aircraft and other military structures are utilized to advantage.

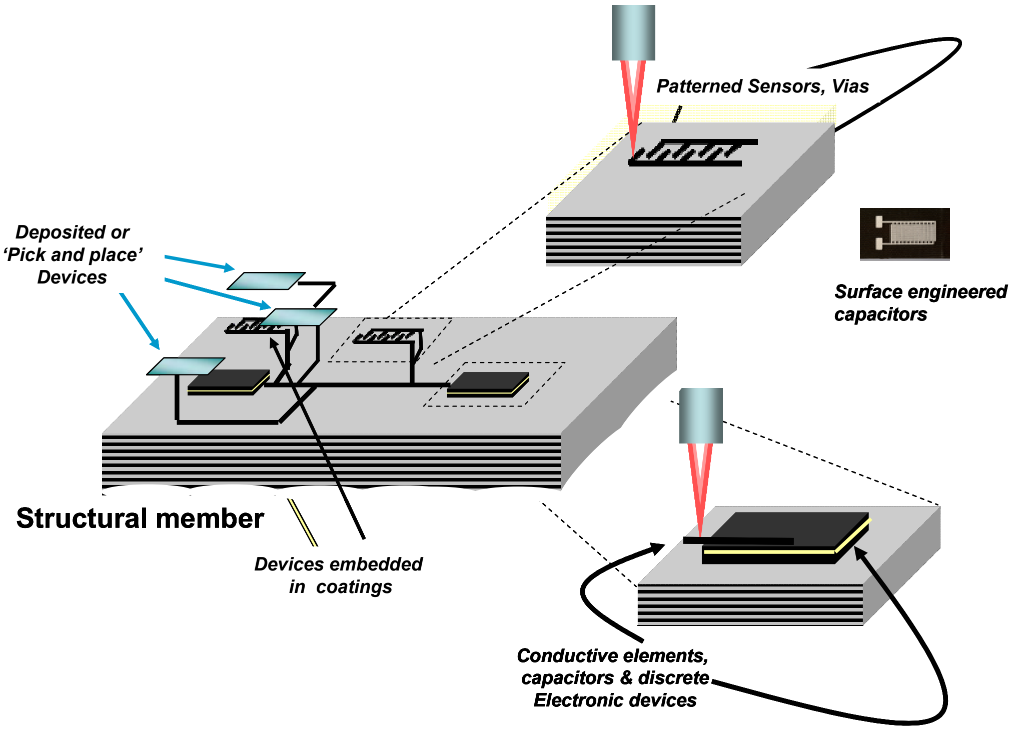

Figure 1: An illustrative example of a surface engineered multifunctional structure. The concept embraces multilayered materials, conformal direct write technology as well as integration of pre-fabricated devices through "pick and place" schemes.

The concept of surface engineered multi-functionality has been made possible through innovative new direct write technologies which have emerged in recent years. For instance, the DARPA Mesoscopic Integrated Conformal Electronics (MICE) program enabled creating of technologies for 3D maskless direct writing of passive components, electromagnetic and sensors. (www.darpa.mil/dso) Various materials technologies have allowed synthesis of layered and graded multilayers which have new design capabilities for surface engineered materials. Synthesis of these technologies with new ideas in device integration and structure design will enable mesoscale surface engineering for multifunctionality.

In this paper we will discuss multifunctional systems within the context of our newly developed fabrication methodology which will allow novel design concepts in integrating sensing/energy storage function directly on a *complex conformal surface without structural or fluid dynamic debits and ease of application*. Specifically we will discuss development of mesoscale multifunctional systems based on a novel adaptation to modern day thermal spray coating technology which will allow not only fabrication of surface layers but also patterning through a breakthrough direct write modification to the technology [3-5].

The surface engineering strategies primarily involves a combination of direct write patterning, thermal spray deposition and laser micromachining to create embedded sensor layers and electromagnetic surfaces. Additional technologies such as *pick and place* of discrete high performance devices, will also be considered future integration concepts to add truly multifunctional materials and system integration.

The advantages of our proposed method include:

- Ability to use planar devices through layered architecture directly onto a conformal surface such an air frame or space craft.
- Materials compatibility and low temperature processing that will potentially achieve a multifunctional system having a primary load bearing component with strategically placed, additively fabricated energy storage, sensor or electromagnetic architecture.
- Integration of lead wires, routing, bus architecture and potentially signal conditioning and logic as part of an integrated architecture.
- Layered design may potentially allow for some load bearing possibility, although the principle target here is to minimize the weight through precision patterning.
- Compatibility with both OEM and Legacy platforms, including both composite and aluminum based structures and airframes.
- Flexibility and tunability with materials, i.e., enabling achieving a variety of functional requirements by simply scaling the number of layers or surface area of application.
- Large area, low temperature fabrication for ease of integration.
- Potential cost effective and rapid insertion, given the base structure design is not significantly modified or expect to be compromised.
- Ability to hybridize various additive and in some cases additive subtractive fabrication methods including direct write, overlay deposition and pick and place components.

The technical challenges (and *potential mitigation strategies)* include:

- *Achieving very high quality functional devices.* This is partly overcome by potentially hybridizing conventional technologies along with fabrication technologies (e.g. pick and place devices hybridized with thermal sprayed interconnect and layer architectures.
- *Limitations in available degrees of freedom for component design*. The proposed approached principally relies on surface engineering and as such explores principally this avenue.
- *Fabrication process and materials optimization can be tedious.* There has been considerable background research in this area which will help accelerate the development cycle.
- *The strategies can be very difficult for highly complex geometry*. Our capabilities will allow for reasonable curvature since the process is line of sight and the design will focus on such surfaces.
- *Environmental effects and degradation*. Surface layered devices can be protected by coatings to prevent environmental degradation and in fact can be benefit for extreme environment situations.

This feasibility of implementing the above concepts is discussed within the framework of three device examples.

2.0 ILLUSTRATIVE EXAMPLES

A. Multifunctional Surface Engineered Structural Capacitor

It has long been recognized that one of the most promising applications multifunctional systems applications is in power harvesting and storage. Beyond the traditional propulsion power requirements, modern combat systems have needs to support power management for wide ranging electronics and sensor applications. The requirements for such applications can be multimodal from those that require short bursts of large energy to those requiring prolonged supply of low range power to operate sensors and electro-magnetics.

There are several concepts under consideration for energy harvesting including solar cells, vibratory harvesting and RF power scavenging methods. A number of these ideas are under consideration around the world. Furthermore it is also important to develop technologies for power storage so as to meet "*on-demand"* requirements when and where it is needed. Energy storage concepts include batteries, fuel cells on the one extreme for continuous power applications to capacitors for rapid release applications.

Mesoscribe Technologies is examining the feasibility of building a MSE based structural capacitor using a combination of direct write, thermal spray and pick & place technologies. Since capacitance is directly proportional to area and inversely proportional to thickness, a surface engineered capacitor is a natural fit to explore the concept. A schematic of a surface engineered structural capacitor is illustrated in Figure 2. It comprises of conformal "sprayed on" dielectric materials with appropriate interconnect architectures built in. Although our fabrication technology enables both interdigitated and parallel plate capacitors, the latter concept offers the most promise in terms of power storage density.

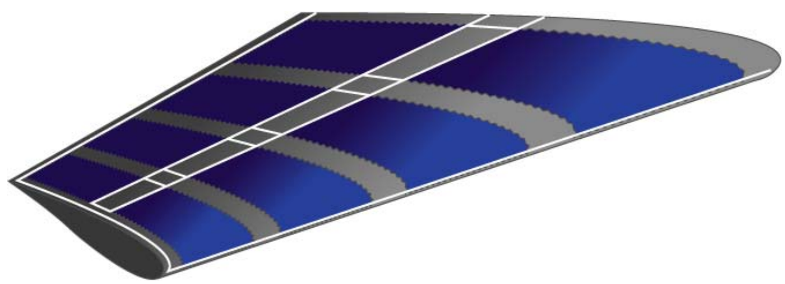

Figure 2: Schematic of a multifunctional structural Capacitor concept on wing of an aircraft. Note 'patch' based approach, rather than single monolithic capacitor for redundancy. Figure shows how they might be connected electrically. Our proposed technology can fabricate both the patches and electrical interconnects with the same tool.

A wide range of dielectric materials are available for examination. They include low K polymers to high K materials such as Ta_2O_5 and $Ba(Sr)TiO_3$. Each system offers its own set of complexities in terms of dielectric properties and will need to be considered within the constraints of the systems issues including structural attributes.

A key requirement for rapid discharge applications is the ability for large storage of power. As such the capacitance requirements can realistically be achieved by incorporating very thin dielectric layers. The mesoscale approach described through the thermal spray approach is not likely to achieve such thin structures. In these circumstances, a consideration would be to build discrete devices through traditional manufacturing technologies (thin films, sintered ceramics etc) with a concurrent goal of pick and place integration of these externally fabricated devices through the surface engineering architectures. No doubt numerous issues of alignment, placement, speed and bonding arise which requires careful consideration.

A unique attribute of the MSE multifunctional concept for structural capacitors is the ability to integrate the interconnect architecture within the assembly. Illustrative examples of such strategies is presented in Figure 3. Conformal direct write technologies will allow patterning either below or above the capacitor tile structures the interconnect framework. Incorporation of switching devices will facilitate operation of a charge and discharge mode as shown.

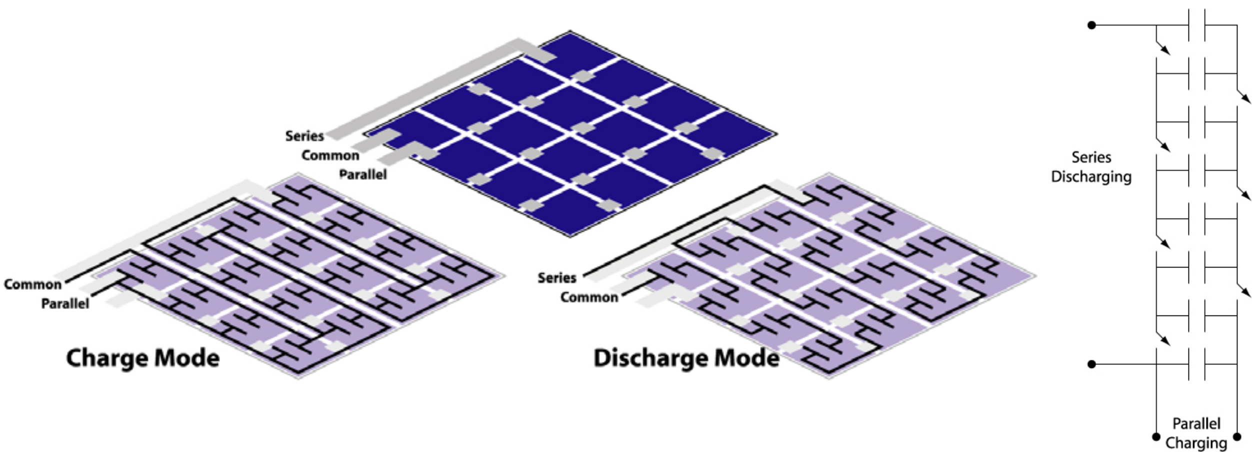

Figure 3: A "Tile" or "snake skin" architecture of a structural capacitor along with the charge and discharge mode interconnect architecture. In this illustration, the charging circuit is accomplished in parallel mode while the series circuit can be used for rapid discharging. Additional description below.

The proposed concept serves as an illustrative example with the following features.

- A planar array of multiple capacitors (shown dark blue). The capacitor can be a thin film, thick film or a multilayer architecture to appropriately tune the required capacitance. In our proposed approach one can envision either a thermal sprayed dielectric or a pick and place thin film device with large capacitance.
- A parallel arrangement is used to charge the capacitors e.g., using a battery or solar cell.
- A serial arrangement is used for rapid discharge i.e., high power, supply *from* the capacitors through a load (like a motor or servo).
- To toggle n capacitors from a parallel to serial configuration requires (n-1) switches (shown as overlapping grey squares).
- Two modes are shown schematically, overlaid on original design.

This approach can also be optimized for structural design, notably compliance of multilayers to accommodate dissimilar materials in terms of physical properties. The *snake skin or tile structure* provides for designed in compliance as well as redundancy. The charge and discharge mode can be configured through a multilayer strategy to reduce the number of switching devices.

Clearly, the presented concepts require careful consideration in terms of both the energy storage and discharge requirements as well as the structural function. Critical activites include design optimization of the surface engineered capacitor structure for both modulur (non load bearing) as well as integrated (load bearing) subsystems. Figure 4 summarizes integration issues. Materials performance consideration and ease of manufacture will no doubt dominate the application requirements. Activities are underway towards meeting this goal through Air Force Research Laboratory sponsored small business innovation research program at MesoScribe Technologies.

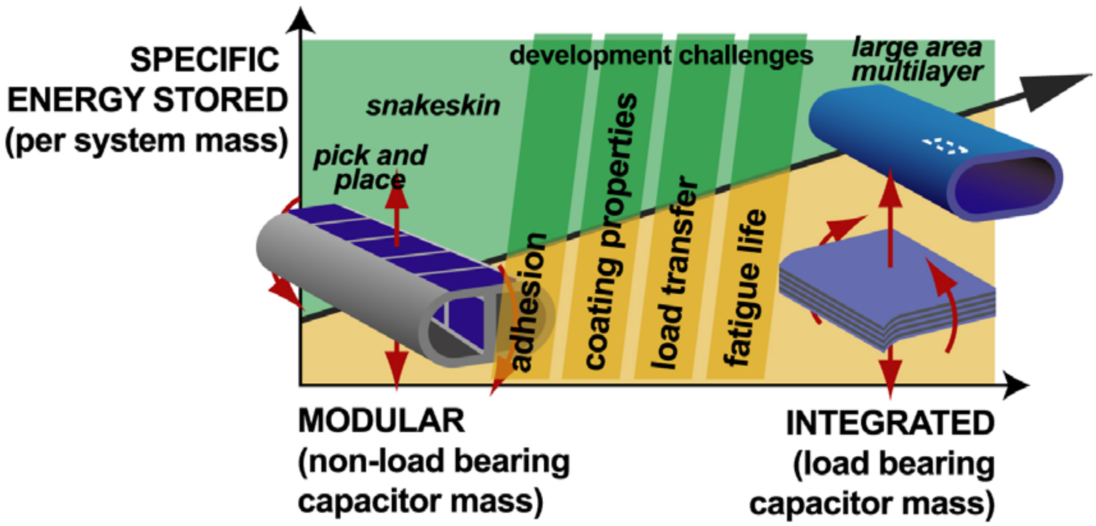

Figure 4: Multi-functional design consideration for a surface engineered structural capacitors.

B: Sensor Integrated Multifunctional Composites

Structural health monitoring of composite structures *in-situ* and in real-time is a vital capability for the US Department of Defense. Sensor laden multifunctional composites has been active an area of research over the last decade. Fiber optic sensors woven into the composite has been one method to sense degradation, strain and other environmental / structural parameters. The MSE multi-functionality approach offers an alternative method to incorporate both deposited sensors as well COTS devices that are packaged within the laminate itself. A key requirement of these strategies is the ability to extract the signal either through wired or wireless means. We are examining methods to directly deposit sensors and electronics onto conformal composite structures, embedded within protective coatings and be made wireless for real-time component state awareness. Wireless, harsh environment sensors that are seamlessly integrated into composite components are integral to successful implementation of actively monitored system components. The sensor data can be reconciled based on *apriori* composite degradation and failure models which can be established through laboratory testing of both the structure and the sensor system. Such an integrated approach of multi-degradation testing, embedded sensing, and damage prediction will provide unprecedented capabilities for structural monitoring and component life prediction of composite structural assets.

Figure 5 shows an illustration of an embedded sensors within a composite and associated interconnect architectures. Additional examples for potential applications is shown in Figure 6, where functional layers are sequentially added via surface engineering so as to provide sensing, and RF wireless interrogative schemes. MesoScribe Tech. in partnership with SUNY-Stony Brook is pursuing such strategies through support from Army Research Office STTR program.

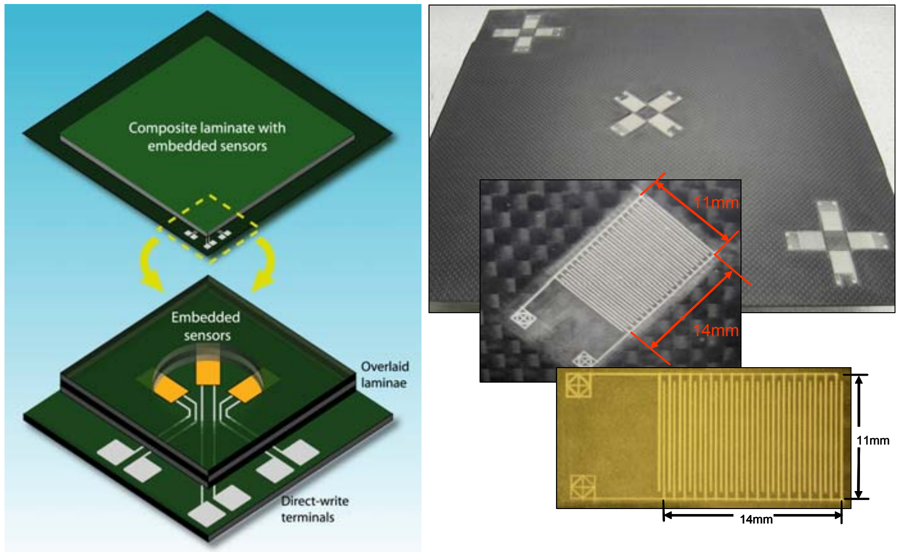

Figure 5: Embedded and direct write sensors in fiber reinforced composites. On left is a schematic of overlaid laminate. On right is a capacitive strain sensor array on a large composite board (2 x 2 ft).

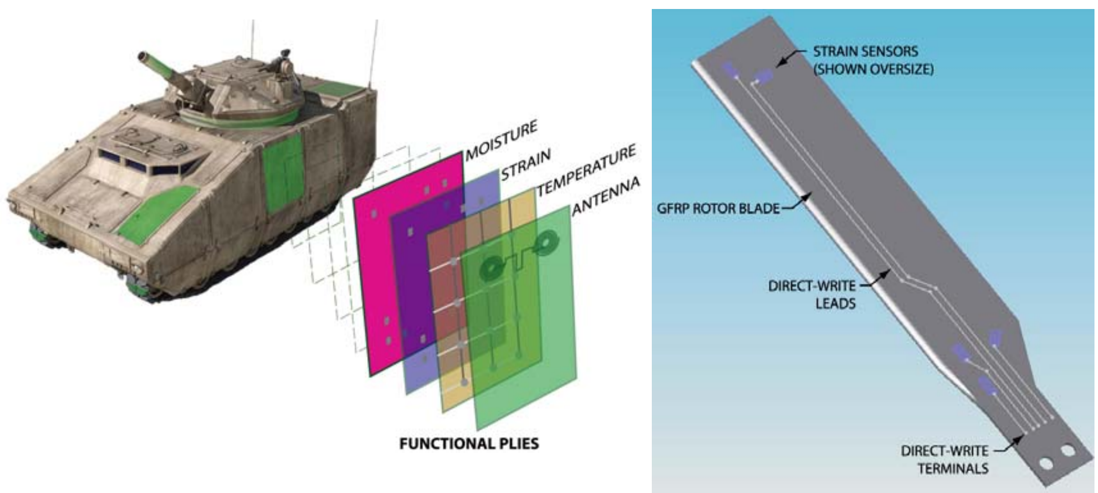

Figure 6: Illustrative examples of a multifunctional sensor suite on a surface. On the right strain sensor illustration on helicopter rotors.

C: Conformal Antennas and Sensors and RF Devices

There is an ever increasing need for conformally mounted antenna arrays in aircraft systems. This includes high frequency, broad-band communication systems for both data and voice in military and commercial aircraft. The performance requirements of these systems adds further complexity in terms of materials, circuit design, geometry and space constraints. Modern low observable aircraft are often made of composite skins and traditional approaches to antenna adaptions are also changing. A typical military aircraft, UAV or missile can have a number of different antennas secured at various locations on the fuselage. In addition to this topic, some examples in the microwave range include:

- Altimeter antenna on the belly of the aircraft
- Wideband ESM single elements or interferometer
- GPS antennas single element and multi-element arrays
- High frequency satellite communication antenna (airborne direct broadcast system)
- Datalink array – Line of Sight and Satellite

The installation and integration of such antenna systems is an expensive task when it requires adapation of planar antenna panels onto curved geometries. The airframe typically is a complicated compound curvature which requires expensive antenna base plate tooling for a precise installation. The nature of the aircraft structure and skin may preclude incorporation of advanced ceramic dielectrics and ferrite materials, which usually are not flexible or moldable and do not lend themselves to complicated curvatures. Utilizing the real estate provided by the aircraft frame will enable a more efficient adaptation of arrays of antennas to the aircraft. Given the complexity in geometry, shape and material limitations of the aircraft structure, it is clear that both conformal antenna development and direct integration/fabrication of such conformal antennas with/on the fuselage represents an important problem for further development within the military community. Additional requirements are to do this reliably, reproducibly and cost effectively.

Advanced antenna systems have complex architecture to provide the requisite performance, gain and directionality. These require intricate patterning of the conductive element on high performance, low loss ceramic or polymer dielectrics which show low parasitic losses at high frequencies. Voltage tunable dielectrics such as $Ba(Sr)TiO_3$ are needed for phased array applications. Thick film ceramic based processing has been the method of choice for a ceramic dielectric based antenna systems, however, this technology generally requires high temperature processing and is primary suitable for batch produced mass market products (eg.cell phones).

Lastly, requirements for a given antenna system for specific applications are constantly changing. The constant development cycle and related implementation can significantly benefit from the ability to rapidly prototype, test, optimize and implement. Needless to say this can be expensive and cumbersome for conformal applications, especially for custom designed, relatively lean volume military applications.

The MSE concept by direct write methods such as thermal spray will enable large area patterning of electromagnetic surfaces and multilayer sensors and RF devices. Our past work has shown that it is feasible to fabricate metallic layers in both patterned and overlaid formed directly on a conformal surface, over large areas. Figure 7 provides illustrative examples of antennas and frequency selective surfaces prepared using this method. Recent work at MesoScribe has performed one on one comparison of conformal GPS antennas manufactured by the thermal spray approach in comparison to conventional means and results are very encouraging. Initial tests indicate that this is feasible means to achieving this goal. This offers unprecedented opportunities in utilizing the large passive surfaces for electromagnetic and sensors functions.

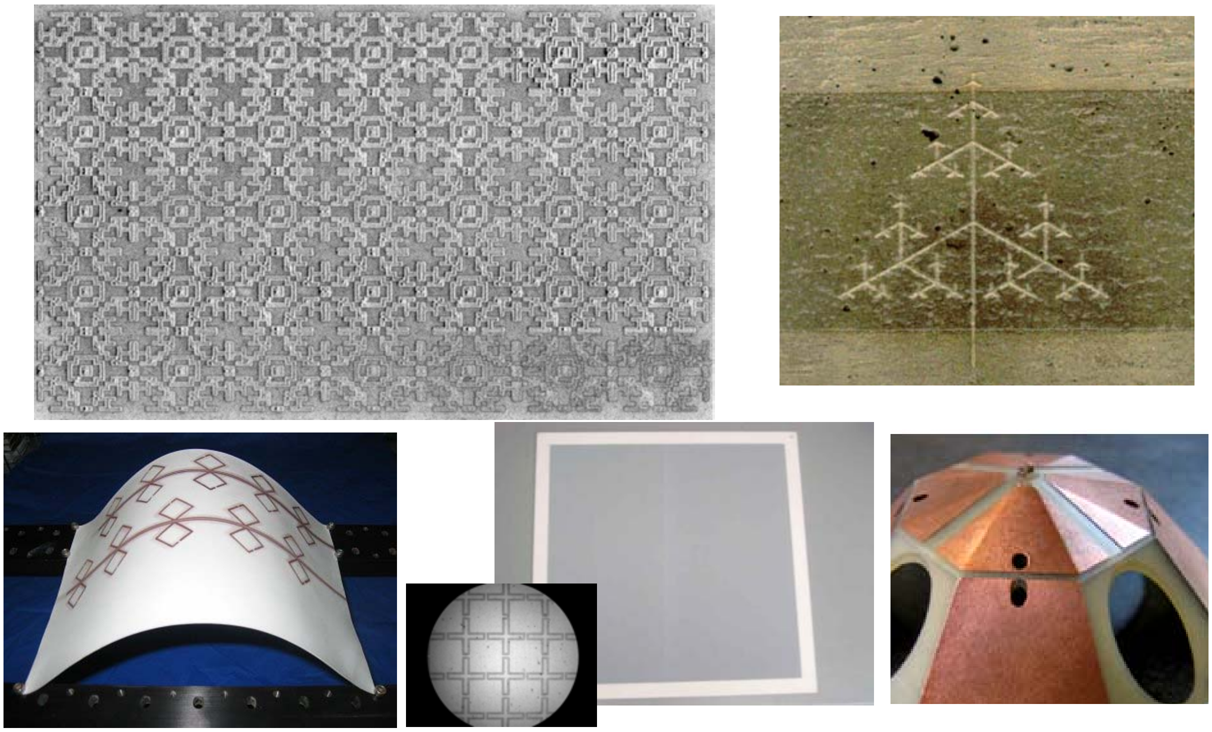

Figure 7: Illustrative examples of direct write thermal spray antennas and frequency selective surfaces obtained directly from CAD files. Top left: Genetic algorithm designed frequency selective surface, top right, fractal antenna on concrete, bottom left large area rectennas. Bottom center, 2 x 2 ft frequency selective surface by additive subtractive technique. Bottom right is an example of a conformal GPS antenna on a radome structure. The antenna performance was compared with traditionally manufactured technique.

3.0 SUMMARY AND CONCLUSIONS

This paper presents concepts in multifunctional systems based on a surface engineered material architecture. The concept is enabled by recent advances in thermal spray deposition as well as the ability for conformal direct write patterning on large areas at low temperature.

As discussed through illustrative examples, the proposed strategy offers potential solutions for multifunctional system applications in energy storage, conformal antennas and embedded sensors. The proposed approach relies on an additive method on top of load bearing passive structures. Challenges to implementation remain in addressing the structural parameters as well as performance attributes of the systems.

ACKNOWLEDGEMENTS

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SYMPOSIA DISCUSSION – PAPER NO: 10

Author's Name: S. Sampath

Question (G. Günter):
Repairability of electronic elements/sensors "written" on structural substrates not removable from the platform in service?

Author's Response:
In principle the process can be used for repairs since it is "instant cure" so no post processing is required. The layer can be stripped and "re-written" if desired.

Question (H. Schippers):
1) Can you give an indication of the minimum thickness of the layers of FC's?
2) Can you give an indication about the accuracy of the process, on planar and on simply curved structures?

Author's Response:
1) Minimum thickness of metallic layers is about 10 µm. Minimum thickness of ceramic layers is about 25 µm.
2) For planar surfaces the accuracy is determined by the motion system(4 µm). The minimum line width is approximately 250 µm +- 25 µm.

Question (B.H. Lee):
What is the maximum size of the area typically covered by this new manufacturing process? Please give a rough estimate of the speed of the process?

Author's Response:
The area is limited by maximum size of automation. At our lab we can currently process 2 per 3 meters. With new robotic ideas, the process can be applied on large objects (aircraft wings , bridges etc). Typical writing speeds vary from 100 mm/s to 500 mm/s depending on material and line qualities.