Nanomaterials and Future Aerospace Technologies: Opportunities and Challenges

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ABSTRACT

Two decades of extensive investment in nanomaterials, nanofabrication and nanometrology have provided the global engineering community a vast array of new technologies. These technologies not only promise radical change to traditional industries, such as transportation, information and aerospace, but may create whole new industries, such as personalized medicine and personalized energy harvesting and storage. The challenge today for the defense aerospace community is determining how to accelerate the conversion of these technical opportunities into concrete benefits with quantifiable impact, *in conjunction with* identifying the most important outstanding scientific questions that are limiting their utilization. For example, nanomaterial fabrication delivers substantial tailorablity beyond a traditional material data sheet. How can we integrate this tailorability into agile manufacturing and design methods to further optimize the performance, cost and durability of future resilient aerospace systems? The intersection of nano-based metamaterials and nanostructured devices with biotechnology epitomizes the technological promise of autonomous systems and enhanced human-machine interfaces. What then are the key materials and processes challenges that are inhibiting current lab-scale innovation from being integrated into functioning systems to increase effectiveness and productivity of our human resources? Where innovation is global, accelerating the use of breakthroughs, both for commercial and defense, is essential. Exploitation of these opportunities and finding solutions to the associated challenges for defense aerospace will rely on highly effective partnerships between commercial development, scientific innovation, systems engineering, design and manufacturing.

Keywords: Nanomaterials, Nanoscience, Nanotechnology

1. INTRODUCTION

Early fundamental successes in the burgeoning field of nanoscience have garnered much attention from researchers, policymakers, and customers.[1,2] Products enabled or enhanced by these nanomaterials are now entering the marketplace. Vast opportunities as yet unexplored for nanomaterials abound, necessitating continued vigorous basic materials research and successful transition to advanced systems. New challenges presented by nanomaterials, including durability, manufacturability, design tools, and health and environmental effects are being indentified and the solutions are still in their infancy.[1,2,3,4,5]

Efforts toward these opportunities are global, with the United States, Japan, and Europe investing approximately equal amounts, and those from China rapidly increasing.[1,6,7] Other countries are focusing

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on niches and are respected world leaders. Overall, commercial investment has surpassed governmental with the largest areas in electronics, biomedical and materials.

Within this framework, the most important challenge for the defense aerospace community is to simultaneously identify the impact of these innovations on current systems, determine which innovations will revolutionize future aerospace capability *and* distinguish those which will not be championed by commercial interests.[8,9] The last factor is especially critical to note: if the defense aerospace community does not take the lead in development of these technologies, they will not be available (or the maturation rate will be unacceptably slow) since either the commercialization risk is too large or the commercial return on investment is too small. Arguably, nanoscience and nanomaterials will have pervasive impact to all aspects of defense systems, ranging from clothing for the solider, to improved structural materials and multifunctional coatings, to never-before-envisioned encryption, data processers and energy sources. For defense aerospace, the impacts will span from structure and propulsion to payload. One of the hardest questions to address is then which of these technologies are defense specific *and* on a critical path to enabling new capabilities. Quantitative answers are crucial. Not only do they provide guidance to optimize investment for development, but they also highlight the most important outstanding scientific questions that are limiting further development. An awareness and dialog across the materials and processing enterprise from low to high technology readiness levels will result in a more rapid convergence of the necessary defense and commercial supplier and manufacturing chains, as well as an acceleration of the maturation and adoption of these technologies in a world in which the science underlying all these possibilities is globally available.

This challenge necessitates a continuing assessment of needs, breakthroughs and their intersection. The following provides a recent assessment of the key nanomaterial-based technological and scientific opportunities from the perspective of the U.S. Air Force Science and Technology 2030 Vision.[10] From a distillation of the vision, five critical opportunities for nanomaterials to substantially impact sub-system performance and thus capabilities are briefly discussed. This also affords the identification of four pervasive scientific challenges that, if addressed, would substantially accelerate the maturation of nanomaterial concepts into reliable aerospace products.

2. TECHNOLOGY OPPURTUNITIES

Released by the United States Air Force Chief Scientist in 2010, Technology Horizons (A Vision for Air Force Science & Technology (S&T) During 2010-2030) outlines the Air Force's major science and technology objectives through the next decade.[10] It examines not only the "art of the possible" but also considers the strategic, technology and budget environments during this period to determine new capabilities that meet the greatest challenges facing the Air Force. With inputs from a wide range of organizations and sources, including the Air Force S&T community, Major Commands, Product Centers, defense industry, and academia, this S&T vision articulates the overarching themes and grand challenges along the path toward the most critical technology areas and associated potential capabilities. The findings and recommendations reinforce the mission of the defense aerospace community to deliver systems that enable the ability to achieve *universal situational awareness*, to *deliver precision effects anywhere*, and to *access and survive in the battlespace*.

A major conclusion of the study is the need for science and technology to simultaneous deliver capability increases, manpower efficiencies, and cost reductions – any one is not sufficient, all three are necessary.[10] Key platform technologies, including engineered resilient systems, autonomy and human systems, are envisioned to emerge from the integration of future innovations in hardware, software and informatics. Bottlenecks in any of these areas will ultimately limit the capabilities delivered by these platform technologies. Availability and knowledge of materials and processes will be one of the major factors setting these limits by restricting the feasible design and manufacturing space. As such, materials innovations and streamlining the materials enterprise system are paramount to transforming Technology Horizons from a vision to reality.

Nanomaterial successes provide a rich and expanded suite of options across this spectrum of platform technologies. To ensure materials are the enabler and not the limiter, a key future tenant of materials research and development is to establish *and digitize* the complete relationship between composition, structure, and processing with regard to performance. Rather than a heuristic understanding of sub-aspects of the interdependence of structure-processing-properties, the design and manufacturing of these platform technologies will require verified and validated packages containing the complete structure-processing-properties relationship. As such, nanomaterial design and optimization can occur in conjunction with device design and optimization. These needs are aligned with recent emphasis on integrated computational material science and engineering, such as by the Materials Genome Initiative.[11]

Based on these needs, and consideration of recent innovations in nanomaterials and their intersection with bio materials and meta material concepts, five key opportunities for substantial impact of nanomaterial innovation on the key platform technologies discussed in Technology Horizons have been identified. These include:

- Multifunctional and Adaptive Structural Materials
- Responsive Sensors
- Integrated Energy Generation and Storage
- Human Performance Monitoring
- Information Processing and Storage

Multifunctional and Adaptive Structural Materials

Future unmanned systems, whether they are for close-in support, stand-off surveillance or providing rapid access to space, will require more from structural materials than simply being lighter, stiffer, and stronger. Improving on performance objectives requires stringent control of weight and volume while delivering additional functional performance. Thus, designers are required to consider the structural integration of functions such as sensing, actuation, communication, energy storage, electromagnetic (EM) protection, energy harvesting, and thermal management to decrease parasitic weight while delivering improved specific performance. Driving mass out of a system directly leads to increased efficiency for the same performance, or increased performance for the same efficiency. As platforms become increasingly miniaturized and/or adaptive to the environment (e.g. morphing micro-unmanned aerial vehicles), integration of function at the materials scale will be even more beneficial. For example, in comparison to a fixed wing aircraft, an intermediate configuration morphing aircraft has the potential to increase both endurance during loiter and time-to-station dash for an overall improved surveillance function.[12] However, this technology has been limited by the availability of material systems that readily and reversibly transform from being sufficiently rigid to pliable so as to enable the envisioned reconfiguration. Nanomaterial concepts for multifunctional and adaptive structural materials hold promise in providing solutions to such challenges.

Multifunctional structural materials are designed to deliver structural performance as well as serve other functions. Building on decades of materials-design paradigm established by the composites community, nanomaterials provide a promising tool to add functionality or address a weakness within these highly engineered composites at a finer length scale. For example, inclusion of nanoparticles between plies can enhance resin-rich properties, such as inter-lamellar or compressive strength, which often limit the ultimate application and design. Inclusion of nanomaterials into coatings or resins will increase the conductivity of the outer surfaces with minimal additional weight, enabling protection of structures and subsystems. For example, lightening strikes produce considerable damage to composite aircraft and their subsystems, challenging all-weather operation. Existing solutions to increasing the conductivity of composite aircraft involve adding metal "chicken wire" to the surfaces, which adds significant weight and maintenance cost. Nanomaterial approaches to lightning strike protection and EM shielding of spacecraft have already been demonstrated using nickel nanostrands and other conductive fillers [13].

Adaptive materials are those that have the ability to alter their physical properties in response to an external stimulus in a controlled, reversible, and repeatable fashion. At this point, fundamental properties of adaptive materials such as polymer nanocomposites are tenuously understood and difficult to predict. A controlled and predictable response is dependent upon obtaining consistent materials and morphology, and a fundamental understanding of the behavior. Current efforts focus on determining structure-property relationships to enable predictability for far-term adaptive structures and programmable matter. This includes nano-based sensing concepts that would initiate or control an adaptive response; energy transduction schemes and network-like morphologies that provide for a designed non-linear mechanical response; and nanomaterial based substrates and hinges for responsive origami concepts. For example, polymer nanocomposites represent a potentially significant improvement for multi-functional shape memory polymers through the distributed energy transduction provided by nanoparticles. As a result, morphing materials can potentially be triggered to change shape with less energy and more control [14].

Responsive Sensors

To provide decision-makers with increased situational awareness, the vision of layered sensing argues for a single, networked operational capability that integrates intelligence, surveillance, and reconnaissance assets. Substantial improvements in sensitivity, cost, and reliability of a vast array of sensors, emitters and communication devices will be needed to attain this vision. These advanced sensors for defense aerospace-unique activities may be initially divided into two main categories: responsive reporters and extreme EM sensitivity devices.

Responsive reporters place a premium on affordability, with reduced performance but extremely attractive performance to cost ratios. These low cost sensors will be utilized primarily on the ground, be nearly disposable, with basic “diode-like” performance to act as simple yes/no indicators. Nanostructures provide unique ways to engineer the transduction of an event into an observable signal. Utilization of nanomaterials in these devices will enable improved responsiveness due to the small length scales for diffusion of the agents to the sensing materials. Current work focuses on signal transduction mechanisms and encapsulation methodologies to improve lifetime. These nanosensors may be individual devices or integrated into spray-on coatings for structures, vehicles, or fabrics to detect chemical, biological, or explosive agents [15,16,17]. These types of sensors will be revolutionary because they will enable ubiquitous deployment of sensing capability to provide early warning detection.

Sensors with extreme EM sensitivity prioritize performance over cost. These sensors are utilized on air and spacecraft for image and signals intelligence. Instead of detection of chemical, biological, and explosive agents, these sensors operate through detection of electromagnetic radiation. Depending on the specific application, different ranges of the EM spectrum are required. Most importantly, these sensors must be appropriately sized for aircraft or spacecraft payloads. Through quantum confinement effects, nanostructures such as quantum wells, superlattices, quantum dots, and carbon nanotube arrays, will enable vast improvements in sensitivity and temperature of operation. Cost, reliability, and size will be addressed through miniaturization of electronics and improved manufacturing processes.

Integrated Energy Generation and Storage

Energy generation, storage and conditioning are arguably the most pressing concern facing long-duration surveillance concepts. For example, mission duration of micro-unmanned aerial vehicles (μUAVs), primarily used for intelligence, surveillance, and reconnaissance, is limited by the amount of energy payload that can be carried. Current μUAV operations ultimately rely on the available supply of batteries or fuel. In remote forward locations this presents not only a logistical and cost burden to the services, but a threat to the soldiers needed to deliver them by convoy. UAVs that can harvest solar energy from their surroundings would present a remarkable advantage over current systems, since mission duration would be substantially expanded. Current work in nanomaterials for this application focuses on improving the efficiency of lightweight, pliable form factors that can be fitted over the surface of UAV wings to provide sufficient power for propulsion and sensor packages. Nanomaterials provide distinct advantages over traditional materials because the dimensions of the fundamental processes involved in light conversion to electricity are on the nanoscale, and tailoring the dimensions of the devices to that scale can provide substantial increases in efficiency. However, simply providing new energy harvesting capabilities will not be sufficient. New energy storage architectures with improved energy densities must also be developed to provide energy for times of peak usage or night missions. Current battery form factors are not ideal; they are relatively heavy and have non-ideal architectures. The development of improved energy density batteries with tailorable architectures would provide the ability to incorporate conformal batteries into a μUAV structure. Long-term, nano-structured and hierarchical batteries may be expanded to multifunctional systems, simultaneously delivering energy harvesting, storage and structural functions. For example, carbon nanotube papers, already used for ultracapacitors, could serve a second function as a structural component or a wing skin [18].

The power requirements of today's aircraft are significantly greater than those of previous generations. The development of higher performance aircraft with increased control, surveillance, and other electronic subsystems has added to the total power required. Long term desire to replace hydraulics with solid state actuators will further increase power demand [19]. With these additional power requirements come added system complexity and power conditioning needs, which will add undesired mass and subsystem volume to the aircraft. The development of improved energy storage and power conditioning materials and devices, including capacitors and inductors, is critical to meet these emerging electronic needs. For example, to overcome the disparity between high energy density and high power density, scientists and engineers are investigating nanomaterial solutions that may improve the energy density of capacitors by improving the dielectric material strength, decreasing loss, or developing materials to withstand higher voltages and temperatures [20].

Human Performance Monitoring

Defense aerospace operations will always occur with a human in the loop. The effectiveness of a mission is inevitability linked to the effectiveness of these human operators. Presently, many aerospace systems incorporate information about the state of the equipment into mission planning and execution. Including information about the state of the human into these decisions will enable the optimization of the interface and information flow between human and machine, as well as increase our ability to protect the warfighter. For example, monitoring the in-flight blood oxygenation of F-22 pilots provides both pilot and platform safety [21]. Similar benefits are anticipated for critical and stressful ground-based applications, such as remotely piloted vehicle operators and air traffic management controllers, as well as physically stressful missions, such as first responders.

Current physiological and biological sensors are standalone devices with bulky form factors. In some cases, sample collection, fluid handling, biochemical analysis and electronics for processing, communications and data storage are actually executed by separate devices. For example biological sensors for glucose or heavy metal poisoning are typically implemented using pharmaceutical processed sensing elements or laboratory instrumentation. Form factors for warfighter monitoring however must be integrated, lightweight, and comfortable to avoid disrupting mission activities while ensuring user acceptance. A flexible, disposable patch solution poses a number of integration challenges, such as combining disparate sensors, microfluidics, communications, and power on one substrate, as well as providing a flexible system architecture and manufacturing approaches to allow introduction of new technologies at low cost. Forward-looking manufacturing technologies must be compatible with sensitive biological materials yet support the functionality of conventional electronics. Manufacturing must also be affordable using high-volume, high-throughput processes to meet anticipated warfighter and consumer application demands. Recent demonstrations of analyte detection at parts per billion concentrations with a combination of peptide or aptemer recognition elements and high surface area nanostructures are highlighting promising future avenues of research [22,23]. Nanoparticle assembly and biomacromolecular conjugation are inherently solution techniques and compatible with print and additive manufacturing technologies. A large array of nanostructure devices, including transistors, memory, antennas and batteries, has been demonstrated with nanoparticle inks and similar manufacturing methods. Future focus on the integration of these successes is likely to deliver a disposable patch solution.

Data Storage and Processing Systems

Due to the exponential growth in size of data sets, advanced systems are needed to obtain meaningful information from the raw data. For example, satellite and aerial surveillance generates extremely large amounts of data that is difficult to analyze by automated processing systems due to the large amounts of noise and ambiguity. Traditional techniques and systems utilized for processing small datasets will be insufficient in the future. Simply scaling current computer architectures or linking together large numbers of computers will be inadequate to handle the rigors of these tasks. Successful future data processing systems and networks will require overcoming challenges resulting from the huge data sets, unreliable components, power consumption and integration of dissimilar systems.

Nanoelectronics devices offer advantages for miniaturization and due to very high mobility potentially high frequency electronics, for example with graphene or carbon nanotubes [24]. These devices may overcome the major hurdles to simple scaling of device density. Optical circuitry is also of great interest for data processing applications. Nanomaterials-based storage technologies seek to dramatically improve storage capacity through various means, including self-assembly of polymers, nanomagnetic devices, spintronic devices, memristors, and phase change materials. Substantial development of these technologies is underway in private industry, which will lead to commercial off-the-shelf solutions for many defense needs, such as large scale image processing, battlefield asset management, and complicated network analysis. However, defense aerospace systems operate in extreme temperature and radiation environments which will necessitate substantial research to understand durability, reliability, as well as effective packaging of these developments.

Overall, future focus within these areas on clarifying performance requirements, ensuring producibility and development of verified and validated design tools is necessary to aim future science and engineering at risk reduction and clarification of the cost-performance-durability trade space. In all cases, obvious opportunities in commercial transportation, energy, medicine and environment markets parallel the defense aerospace priorities, emphasizing the win-win potential with commercial-defense partnerships to accelerate development and integration of nanomaterial solutions.

3. PERVASIVE SCIENCE CHALLANGES

The applications and nanomaterial opportunities discussed above are exceptionally varied. Nevertheless, a few general science challenges can be articulated that pervade the necessary developments. Overcoming these challenges will have wide and far-reaching impacts. Four specific challenges can be indentified that revolve around the convergence of Nano with Bio, Info and Manufacturing Science. These are:

- How to precisely control interface, size and structure at the nanoscale
- How to exploit dynamics at the nanoscale
- How to embrace informatics concepts for nanoscale design
- How to validate nanoscale design and manufacturing tools

The first challenge is how to precisely control nanoparticle interfaces, both with regard to the nanoparticle synthesis and integration. This includes interfacial composition and location of modifying agents, as well as the structure and crystallographic orientation of facets, the density of defects and the position of atomic elements. Key is developing characterization tools and fabrication concepts that provide site-specific information of composition and structure at these extremely small dimensions, rather than ensemble averages.

In parallel, determining how to harness the specificity of biomacromolecules and translate this functionality into a broader material palate is crucial. Overall, atomic and molecular level control at the interface is a precursor to everything from revolutionary catalysts for energy generation to exquisite directed assembly of nanoarchitectures with application ranging from sensors to data storage and processing.

The second challenge is how to create nanomaterial designs that exploit dynamics at the nanoscale. A potential opportunity to overcome this challenge is to utilize phase changes in defined geometries which can be actuated through an external stimulus, such as an electric field, magnetic field, heat, light or chemical potential. Additional design motifs may utilize reaction-transport coupling or transport of mass and energy in nanostructures. However, *a priori* structure optimization for a desired responsivity is compromised by the lack of site-specific temporal resolution of events within nanostructures, the ability to measure changes in local field distributions, and associated models. By developing tools to exploit changes between stable and meta-stable configurations, it may be possible to move towards a “material device” concept that mimics the macromolecular-based functionality of cellular processes. Achieving designs that exploit dynamics at the nanoscale will fully enable autonomic responses.

The third challenge is to how to embrace informatics concepts. Informatics technologies developed for image recognition, syntax recognition, searching of unstructured data sets, robust decision making, complexity theory, and network analysis must have important applications to nanomaterial design. What they are and how to most effectively utilize them though are open questions. As an example, when are competition concepts within a large data set containing random fluctuations (evolutionary selection) more appropriate to yield an optimized material design, than traditional linear process (scientific method)? There will be enormous utility in the creation of design tools to synthesize large data sets and analyze them to overcome length and time scale challenges – from laboratory experiments and computer modeling to manufacturing processes and sustainment.

The final challenge is how to validate both nanoscale design tools and associated manufacturing techniques and controls. Particularly relevant are manufacturing reliability, assembly and morphology control, providing adaptive control of the manufacturing process, and fabrication to performance specifications. Current nanomaterials research is largely Edisonian – trial and error, based on a few guiding principles. Historically, trial and error approaches to new material development for the extreme conditions of defense aerospace, which are not frequently seen in other applications, is expensive, cumbersome, and lengthy - if not impossible. Universal tools for validation of nanomaterial development will greatly accelerate the pace with which this type of work moves forward and enable cost-effective materials insertion into next generation systems.

4. CONCLUSION

In summary, after two decades of extensive investment in nanomaterials, nanofabrication and nanometrology the challenge for the defense aerospace community is determining how to accelerate the conversion of these technical opportunities into concrete potential and quantifiable impact. To do so, the most important outstanding scientific questions limiting their utilization must also be indentified in parallel. The defense aerospace community must take the lead in development of those technologies where the commercial risk is too large or the commercial return on investment is too small. Otherwise, they will not be available, or the maturation rate will be unacceptably slow. Exploitation of these opportunities for defense aerospace will rely on highly effective partnership between commercial development, scientific innovation, systems engineering, design and manufacturing. Where innovation is global, accelerating the use of breakthroughs beyond the historical pace is essential.

To further refine the focus for defense aerospace and identify the key science and industrial partners, one must also consider the potential and associated markets seeing similar technological opportunities. For example, potential technological opportunities may fall into one of three categories: commercially-developed technologies; defense-unique technologies; and, commercially-developed but defense-modified technologies. Aerospace defense-unique technologies are those in which the community has a solitary or unique interest in the technology. In effect, there is little to no commercial market for these technologies. If the defense community does not take the lead in development of these technologies, they will not be developed. On the other end of the spectrum, private industry will lead the creation of commercially-developed technologies, due to their non-aerospace-market potential. The defense community will not have to invest heavily in the fundamental research and development of these technologies. Transferring these technologies to warfighter capabilities will focus on system integration issues. The last category lies in between these two extremes, in which there will likely be commercially-led development of a platform technology but it will require substantial additional development to meet unique defense use or environmental demands. Substantial win-win opportunities abound for cross-fertilization and joint defense-commercial development partnerships.

Based on the key platform technologies identified in the 2010 Technology Horizons Report (A Vision for Air Force Science & Technology (S&T) During 2010-2030), five critical opportunities for nanomaterials to substantially impact sub-system performance are briefly discussed. Additionally, four pervasive scientific challenges were identified that if addressed, would substantially accelerate the maturation of nanomaterial concepts into reliable aerospace products. These conclusions provide a basis for an active, continuing dialog between the various stakeholders in the aerospace material development enterprise and commercial market. Continuing to assess the needs, breakthroughs and their intersection will accelerate the incorporation of these opportunities into next generation systems and capabilities.

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