Concept Paper A07
Composite Materials with Embedded Sensing

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Abstract

This report focuses on two examples of Micro-Nano Technology (MNT) in an attempt to plot the way forward for commercializing these MNT devices. The first example is one that has recently gone from a research idea and prototype (2000) to commercialization (2003) and the second is a recently developed (2004) composite suggested here for commercialization. The first example is a Marco Fibre Composite™ (MFC) actuator and sensor invented by NASA Langley Research Center in a quest to develop a high force actuation system for use in helicopter blade control applications. The MFC was successfully commercialized and is now readily available from a sensor/actuator company (www.smart-material.com). However commercializing applications that incorporate the MFC system could be further developed and are yet to be commercialized. The second material considered here, which is not yet on the market, is the recently invented Metal Rubber™ developed by NanoSonic Corporation. Metal Rubber serves as a flexible sensor, or conductive polymer. Suggestions for the steps to take to commercialize Metal Rubber are presented.

Each of these two composite materials is described in detail in terms of their function. This is followed by descriptions of the use of these devices in several applications consisting of Structural Health Monitoring (SHM), Vibration Suppression (VS) and Power Harvesting (PH). Applications are key to developing a successful product and business plan based on new sensing and actuating concepts. These potential applications also provide motivation for new uses and new materials. MFC technology has been integrated in a number of laboratory prototypes, but these applications are yet to be commercialized. The Metal Rubber concept needs to first go through the characterization and prototype development stages before applications towards SHM, VS and PH.

1. Rationale for Recommendation

Flexible actuation and sensing materials that can be fully integrated into oddly shaped structural members have numerous applications for use in aerospace systems to provide solutions to vibration problems, structural health monitoring problems and even to provide power from ambient conditions. Each of these application areas has potential commercial value for providing cost savings, improved performance or improved system reliability. The recommendation here is that Marco Fiber Composite Actuators should be commercially packaged in structural health monitoring applications and that Metal Rubber could be developed into a commercially available sensor material.

The rationale for considering these two technologies is motivated by the substantial sensing business that currently exists. Each of these two systems offers abilities not currently available in other sensing systems for materials and these are highlighted in the following.

2. Current State-of-the-Art

Over the past decade, the expectations of aeronautical systems have continued to demand significant increases in flight time, service life, and adaptability for multi-phase missions without sacrificing payload capacity, additional structural weight, or reliability. Such expectations drive technological advances in the area of composites and multifunctional materials. Multifunctionality, according to Matic (2003), “is about reducing the physical distance between subsystems and coupling the functions different subsystems perform.” The blending of multiple subsystems into a single material or structure reduces overall system mass and size while simultaneously increasing system performance and functionality. Such trends propel the drive behind technological advances in multifunctional materials.

Matic (2003) provides three classes of multifunctionality and designates them as Types I, II, or III. Type I multifunctionality is the addition of subsystems to provide additional performance enhancement to a primary or critical function. Most smart structures would be considered Type I multifunctional systems. Type II multifunctionality is the union or co-location of functions embedded within a system component. Type III multifunctionality is the integration of functions shared in a volume of material. The progression from Type I to Type II to Type III multifunctionality also represents the desired technological track in the overall design course of multifunctional structures. For example, surface mounting a structural health monitoring system to an airfoil would be a Type I; whereas a load bearing, health monitoring sensory skin shaped as an airfoil would be a Type III. A summary of the characteristics of Types I, II, and III multifunctionality is given below in Table 1.

Table 1*. A summary of the defining characteristics of the three multifunctionality types (Matic, 2003).*

Type I Multifunctionality: Added Subsystems
• Subsystem addition to provide additional performance • Connectivity or links between subsystems • Increased physical or informational coupling between subsystems
Type II Multifunctionality: Co-located Components
• Component co-location to provide packaging integration • Reduced dimensionality and complexity of final system • Physical distances between subsystems are reduced
Type III Multifunctionality: Integrated Materials
• Material Selection based on a set of properties to satisfy more than one subsystem function • Physical volumes of subsystems are combined • Reduced volume and mass of final multifunctional subsystem

The International Society for Optical Engineering (SPIE) has sponsored a multifunctional materials segment as part of their Smart Structures and Materials conference for over a decade. In the more recent literature, researchers are focusing on the transition between Type I and Type II systems to the Type III systems. At the Naval Research Laboratory, Thomas et al (2002) focused their research efforts into extending the flight time of a DARPA sponsored unmanned autonomous vehicle (UAV). One concept Thomas et al (2003) pursued was the development of structure-battery materials. In brief, commercially available plastic-lithium-ion batteries that come in thin (~0.5 mm thick), flexible sheets were combined with other structural materials to create a load-bearing wing that also doubled as the power supply for the electric propulsion system. Their work also serves as a prime example of extending a Type I multifunctionality (the plastic-lithium-ion battery) to a Type III system (using the battery as a load-bearing support structure). Another area of research is the use of structural materials as consumable propellants, sometimes referred to as autophagous materials. Qidwai, Thomas, and Matic (2003) also discuss the concept of structure-battery design. Joshi et al (2003) designed structural polymer composite materials that can be converted into combustible fuels once on orbit. Elzey, Sofla, and Wadley looked into using shape-memory alloys in the structural design of an aircraft wing for morphing capabilities.

It is also important to recognize that multifunctionality can occur at different scales. Material scientists and engineers are trying to construct new polymers and ceramics that exhibit desirable traits in the macro-world by layering materials at the nano-level atomic scale. For example, in 1989, a multifunctional materials symposium of the Materials Research Society outlined the design of ceramic composites, silica optics, and piezoelectric composites at the nano-level (Buckley et al, 1989). Similarly, Varadan (2001) discusses the design of MEMS and NEMS based smart chips with embedded carbon nanotube technology to impart superior structural, electronic and surface quality properties.

The current state of the art in MNT sensors examined here comes primarily from the field of smart materials and structures. A review of such systems is given in (Chopra, 2002). One of the main sensing and actuation materials has been based on the piezoelectric effect, which has been commercialized in a number of different forms and used in a variety of applications. The device examined here is also piezoelectric based and uses piezoceramic fibers combined in a unique composite at the macro level to produce a relatively high force, yet flexible actuator and sensor (Wilkie, et al, 2000). The second material system examined here is Metal Rubber™ (Popular Science 2004) developed using a nano technology a molecule at a time. These two devices are shown in Figure 1.

Figure 1 MFC Actuator (left) and Metal Rubber sensor material (right)

Depending on the way it is formed, this Metal Rubber may be used in several ways. In one form, it is electrically conductive and mechanically pliable, and may potentially be used as a flexible electrical interconnect grid between multiple discrete flexible or rigid sensor or actuator elements. In another form, its electrical conductivity may be made to vary as a function of strain or temperature. In this form, it may be used as a strain or temperature sensing element that can withstand large deformations, on the order of well more than 200% strain.

3. Baseline Use

The baseline uses of the proposed systems focus on three areas of vibration control, structural health monitoring and power harvesting. Vibration control is often necessary when passive means of reducing vibration in structures does not meet performance objectives or an original design falls short of satisfying vibration specifications. Structural health monitoring is emerging as a method of extending the service life of structures that have reached their design life. SHM also provides improved safety and the ability to monitor and warn against impending failures. Power harvesting offers the advantages of enabling wireless transmission of sensor data and hence removing one of the barriers to implementing SHM systems. The unique feature of the two technologies examined here is their flexibility. Many applications consist of irregular surfaces with lots of contours and curved surfaces. For instance in structural health monitoring the ability to put sensing in key places is critical.

4. Leading Aerospace Applications

Leading aerospace applications of integrated sensing include structural health monitoring and control. Both applications require sensor information and place a heavy demand on sensor systems that they not be very complex. Aerospace SHM applications include:

1) Monitoring of aged aircraft as part of live extension

2) Monitoring of new aircraft as part of safety enhancement

3) Monitoring of military aircraft for damage assessment and mitigation

4) Monitoring of ground support systems (such as the shuttle launch tower)

Control applications in aerospace focus on:

1) Vibration suppression of harsh environments to reduce fatigue
2) Enabling control of flexible skins in morphing aircraft
3) Vibration and shape control of large flexible spacecraft
4) Vibration suppression and shape control for adaptive optics

Power harvesting applications in aerospace systems include:

1) Wireless sensing systems in support of SHM applications
2) Supplying power to remote computing systems for processing SHM information
3) Provide longevity to battery operated systems

5. Drivers for Change

The big drivers for change are improved performance and capability, and as enabling technology. Both MFC and MR provide all three. MR has excellent robustness to temperature changes (up to 200° C) and is impervious to chemical attack. Its flexibility offers advantages over other sensing materials because of its polymer stiffness. MFC has more limited flexibility but can be applied to curved surfaces unlike monolithic piezoceramic materials.

6. Summary of Prototype Identification and potential Implementation Plan

The first step in bringing Rubber Metal to the market place is to integrate the material into a number of different applications. The second step is to characterize and quantify the sensor properties of Rubber Metal. The third step is to compare its uses in these applications to currently available and accepted technology in the relevant application area. The characterization set-up is in place and will be started with in next few months.

MFC materials have the potential to be implemented in the three application areas mentioned above (VS, SHM and PH). Many proof of concepts experiments have been performed in each of these areas. In the case of the MFC, these application systems need to be integrated and commercialized.

7. Potential Investment Possibilities and Risk

Investment in these technologies is risky if done without proper clarification of abilities based on proof of concept experiments, clarification of abilities and careful market analysis. Replacing current sensing technology with these MNT devices needs to show a clear advantage. On the other hand, MNT devices can offer solutions where none exist. Such applications in this case are less risky.

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