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PROPOSED RESEARCH

1. Introduction

Aerospace structural systems experience a broad spectrum of environmental and operational loads. Severe and/or prolonged load exposures may trigger the damage accumulation process even in recently deployed structures. The process of implementing a strategy of damage detection for engineering structures is referred to as structural health monitoring (SHM), which seeks to answer questions such as: Does damage exist? If so, what kind? Is the damage local or global (e.g., a large isolated crack or many small defects distributed in the material)? Is the damage in the material or in the joints and connections (or both)? Is overall structural failure likely?

SHM is normally based on non-destructive measurement of responses that change due to damage in the structure. Comparisons of measurements made in a damaged and in a reference state allow inference of the type, location, and severity of the damage. Historically, vibration natural frequencies and mode shapes have been the most common such measurements: macroscopic damage tends to reduce the natural frequencies, and mode shapes may be sensitive to isolated damage. Vibration measurements have been used in many ways for this purpose (Doebling, et al, 1996; Sohn, et al, 2003).

Three important "new" issues/approaches impacting structural health methodology are addressed in this proposal. The first is to treat SHM as a comprehensive, multi-scale phenomenon in which damage detection may be needed over a spectrum of length scales from the microscopic to the macroscopic. Most SHM methodologies focus on limited length scales. The second issue is attributing to damage in joints and connections an importance commensurate with fracture and fatigue damage that develops in the structural material. During the past decade both the SHM and the joint dynamics communities have done extensive research. But SHM researchers normally ignore possible damage in joints and connections and joint analysts normally ignore SHM, as their focus is on developing nonlinear models of joint dynamics. We aim to incorporate nonlinear joint damage modeling into the SHM methodology, and this promises to be an important contribution to the science of SHM. Our third "new" approach is to develop material self-healing systems (SHS) that could repair material damage while maintaining structural integrity. For example, microencapsulated healing agents could be incorporated into a material, such that a propagating crack would burst the microcapsules, releasing the healing agent into the crack, filling the cavity and curing the crack so that failure of the material is avoided. The strategies proposed in this paragraph will be intended for many aerospace structures, including aircraft, launch vehicles, space vehicles, periodic space structures, permanent structures placed on the moon or Mars, and for robotic devices that may patrol these structures to perform SHM.

There are four lines of attack that will be followed in pursuit of the aforementioned SHM and SHS methodologies. These are summarized below.

1) Development of a <u>combined joint/material nonlinear vibration-based methodology</u> capable of crack detection through nonlinear vibration measurement and capable of separating material damage from joint/connection damage. The latter is necessary because changes in vibration properties that would normally be attributed to damage in the material may actually be due to change in the boundary conditions accompanying deterioration in a joint or connection.
2) Utilize recently derived results (Sevostianov and Kachanov, 2002) for the <u>cross-property connections between elastic and conductive properties of materials with defects</u>. These

results allow one to measure the change in a bulk material property such as Young's modulus by measuring the change in the material electrical conductivity. This provides an independent source of information that can be combined with the joint/material methodology in 1) above, enabling joint damage to be separated from material damage. We will also pursue methods for directly relating the cross-property connection results to material damage.

3) Development of a high frequency nonlinear acoustic wave propagation SHM approach (Zagrai, et al. 2006) aimed at early, small-scale damage detection. In addition to global and some local parameters inferred through vibration measurements, the nonlinear ultrasonic methodology will utilize the local nonlinear response at high frequencies for damage detection by monitoring the presence of combination frequencies in the ultrasonic response, which signal the presence of nonlinear effects that accompany micro-damage.
4) Pursuit of the aforementioned methodology for self-healing systems (SHS) in metals, alloys and composites, which could lead to significantly improved safety of aerospace vehicles and structures. Several concepts will be developed and realized, based on the work of Bakhtiyarov and Overfelt (1997 - 2002).

Figure 1 shows how the proposed methodologies relate to each other to form a strategy that covers the spectrum of scales and damage levels.

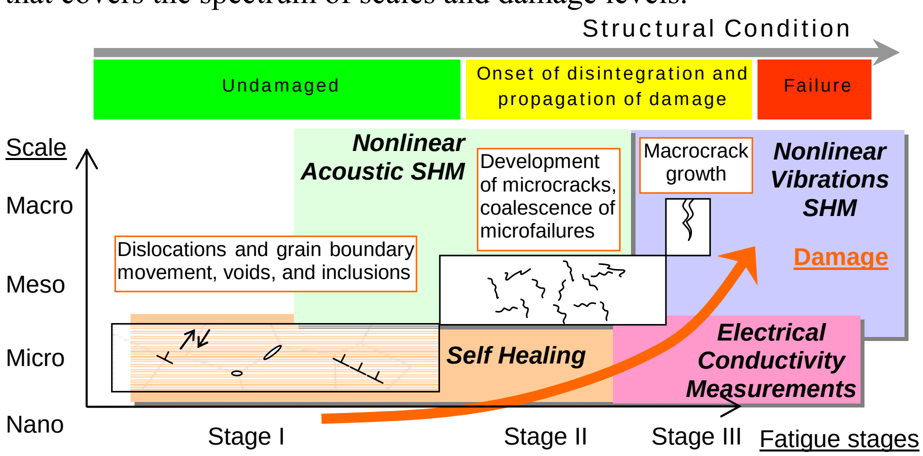

Figure 1 Damage accumulation in a structural system and the SHM methodologies associated with particular damage scales.

Development of the aforementioned SHM technologies combined with self-repairing materials concepts would contribute to economic and social benefits by enabling condition-based maintenance of aged and new aerospace structures and by preventing catastrophic failures and loss of human lives. Our research efforts will be coordinated with the NASA MSFC materials science and structural dynamics teams led by Dr. Benjamin Penn and with the LANL structural health monitoring group led by Dr. Charles Farrar. The proposed project also will benefit the state-funded aerospace engineering (undergraduate and graduate) programs in New Mexico.

2. Objectives

- Develop a methodology for in-situ health monitoring and damage detection of aerospace structures using low frequency vibration and electrical conductivity measurements combined with high frequency embedded nonlinear ultrasonic wave interrogation.
- Develop self-repairing materials for aerospace structures subjected to accumulated damage and use the proposed SHM methods to monitor the self-healing process.

- Contribute to strengthen New Mexico aerospace engineering educational and research programs at New Mexico State University (NMSU) and New Mexico Institute of Mining and Technology (NMT) and use the aerospace programs to interest New Mexico K-12 students in the Science Technology Engineering Math (STEM) disciplines.
- Develop nationally competitive research expertise and research programs in the proposed and related areas in preparation for obtaining follow-up research funding.
- Develop collaborations with key entities in New Mexico, Los Alamos National Laboratory (LANL) Sandia National Laboratories and with relevant NASA Centers, enhancing the prospects for future nationally competitive research.

3. Expected Significance- New & Innovative Approaches

- Improved condition-based maintenance of aerospace structures such as aircraft, launch vehicles, space vehicles and their critical components.
- New approaches to combine various measurement techniques to recover information about multi-scale defects that are accumulated.
- New methods developed for design of self-healing materials to lengthen the life of aerospace structures.
- Starting an interdisciplinary program which brings together expertise in micromechanics, vibrations and non-linear dynamics, materials science, and sensors array technology and controls to solve problems of great importance to NASA.
- The collaboration by five PIs from two research universities in close proximity in a new NASA EPSCoR state which recently started a new aerospace engineering program is significant. A planned state-wide collaboration in SHM that would involve NMSU, NMT, and eventually University of New Mexico (UNM), LANL, and Sandia would position New Mexico to be a world leader in SHM/SHS and related areas.

4. Approaches Technical Discussion of Proposed Research- Work Plan & Preparation for Follow on Research

Presented in subsections (a) – (d) below are technical discussions of the proposed research in the four areas listed in Section 1 (p.2-3). These are followed by a section (e) that defines how the four methods are to be combined into an integrated SHM/SHS methodology and a final section (f) describing the work plan and preparation for follow-on research. In sub-sections (a) – (d) brief reviews of relevant previous research are presented.

a) <u>Vibration based SHM</u>

The focus in the SHM community has been chiefly concerned with the identification of internal damage in structures on either a microscopic or macroscopic scale, with little attention for the integration of multi-scale damage detection techniques or the effects of non-ideal joints and boundaries. Most of the previous work on joints has been concerned with modeling and not on SHM and parameter identification. In contrast, the proposed research in SHM of self-healing structures will obtain and correlate damage information at multiple scales and will utilize existing joint damage models and non-ideal boundary conditions for identification of key damage parameters such as crack size, location, and density. The measurements of vibration frequencies and mode shapes contain combined information on macroscopic fatigue cracks in the internal structure and damage in the joints. Both vibration frequencies and mode shapes are useful for an on-line detection of damage (Imam, et al., 1989; Christides and Barr, 1984; Shen and Pierre, 1990; Yuen, 1985; Shen and Taylor, 1991). The fatigue crack models usually fall into two categories: 1) open crack (linear) and 2) breathing crack (nonlinear) models, which take into account the opening and closing of an elastic crack (Cheng, et al., 1999; Luo and Wu, 2006; Chati et al., 1997). Butcher (1999) has derived a result for the approximate equivalent linear stiffness k_{eq} at the location of a bilinear crack. This approach is well suited for SHM and damage model updating because an equivalent linear model which retains essential characteristics of the damaged nonlinear model can be derived. Recent approaches to crack and damage detection include modal filtering, statistical approaches, and use of the residual force vector (Bahlous et al., 2007; Lam et al., 2007; Yang and Liu, 2007). Expected outcomes work include a new robust SHM technique for crack detection through vibration monitoring.

There are three dynamic mechanisms that are regularly discussed in connection with jointed structures (Bergman and Segalman, 2007): *micro-slip*, *slap* (i.e. vibro-impact), and the transmission and reflection of elastic waves at the joint. Previous efforts in joint mechanics have utilized these mechanisms for modeling purposes only. For instance, the slapping process can be modeled using various compliant models which couple the motions of neighboring masses only under certain conditions (Hunt and Crossley, 1975; Herbert and McWhannell, 1977; Khulief and Shabana, 1987; Luo and Hanagud, 1998; Mills and Nguyen, 1992; Butcher and Segalman, 2000). Our intent is to utilize various compliant boundary constraints which provide a more realistic description of the local structural deformation in non-ideal joints and can incorporate a range of natural frequencies between standard boundary conditions through a combined measurement of frequency shift and energy dissipation. The frequencies of a beam with compliant nonlinear boundaries (e.g. deadzone or backlash) can encompass values from the lowest (for free ends) to the highest (for fixed ends) as in Fig. 2. Results obtained are useful over the entire range between the known solutions, and this breadth is desirable from the SHM standpoint. The proposed procedures enables construction of accurate amplitude-dependent models used in finite element model updating of the damaged structure. Such models typically have large dimension and must be reduced in size. Therefore, some recent order reduction methodologies (Butcher and Lu, 2007; Segalman, 2007; Kumar and Burton, 2007; Kerschen et al., 2005) for systems with localized nonlinearities will be used to accurately represent the damaged structure with a low-dimensional model. Low order models are essential if real time, on-line SHM is to be realized.

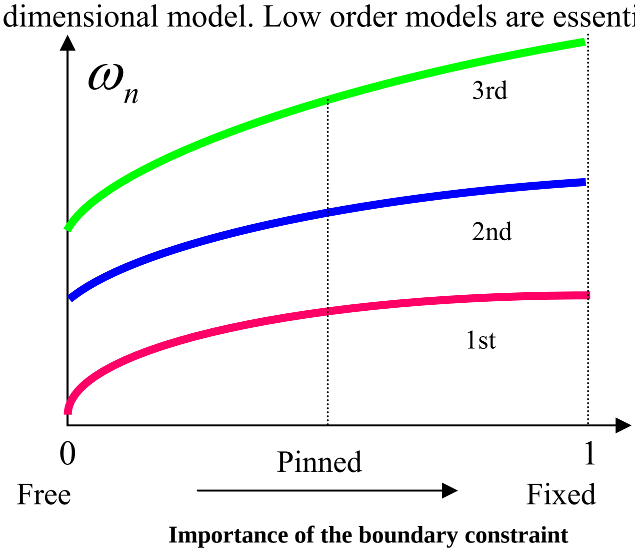

Fig. 2 Schematic of a beam's modal frequencies as a function of the boundary condition

b) Cross Property Connections

The use of electrical conductivity cross-property connections for SHM has, to the best of our knowledge, not been done. In order to apply cross property connections to damaged materials, it is necessary that the theoretical connections utilized take into account the types of material defects that may occur in practice, including anisotropy. The very possibility of such connections – that cover anisotropic cases – is far from obvious: not only are the field equations of conductivity and elasticity different, but the tensors characterizing these properties are of different ranks (2nd rank conductivity tensor *vs* 4th rank elasticity tensor).

The possibility of obtaining cross-property connections has been discussed in the literature for the past two decades. Aside from empirical connections of a curve-fitting nature (see, for example, the work of Kim *et al*, 2005, for metals), the work has focused mainly on establishing cross-property *bounds*, starting with works of Milton (1984) and Berryman and Milton (1988). However, bounding techniques have several limitations that make their application to materials of interest difficult. One of the limitations is that overall isotropy is assumed, whereas damaged metals may have anisotropic microstructures.

Recently, explicit elasticity-conductivity connections have been derived by Sevostianov and Kachanov (2002). Aside from having an explicit form that facilitates their applications to materials science, the results apply to anisotropic microstructures. For example, for *cracks* of arbitrary orientation distribution (general anisotropic case), the cross-property connection takes the form

$$\frac{E_i - E_0}{E_i} = 2\left(1 - \nu_0^2\right)\frac{k_i - k_0}{k_i}$$

where E_i, k_i are the effective Young's modulus and the effective conductivity of a cracked material in certain direction x_i and E_0, ν_0 and k_0 are the bulk material constants. This connection enables the change in stiffness due to microcracks to be determined from the change in the effective conductivity.

The proposed research builds on research in micromechanics of materials with defects and cross-property connections for such materials published by Sevostianov and co-workers in the past 4-5 years (Sevostianov, 2003; Sevostianov and Kachanov, 2002; Sevostianov, et al, 2002; Kachanov, et al, 2001, 2005). Cross-property connections should reflect those microstructural features that have a dominant effect on the elastic and conductive properties. This means identification of the *proper microstructural parameters* in terms of which the said properties are to be expressed. The parameters must represent individual defects in accordance with their actual contributions to the properties, with their shapes and orientations taken into account. For example, for circular cracks of non-random orientations, the (2nd rank) crack density tensor is defined by

$$\boldsymbol{\alpha} = \frac{1}{V}\sum\left(l^3\boldsymbol{nn}\right)^{(k)}$$

where $l^{(k)}$ is radius of the kth microcrack and $\boldsymbol{n}^{(k)}$ is a unit normal to kth microcrack.

Proper quantitative characterization of rather complex microstructures may actually be described by a small number of parameters. For example, a preferential orientation of circular cracks with a scatter is characterized by two components $\alpha_{11} = \alpha_{22}$ and α_{33} of the crack density tensor, that reflect, in an integral way, both the extent of the scatter and the crack density. We plan to develop results of this kind for non-planar crack geometries.

A basic problem in this work is to find the simplest "standard" shapes to which a pore of an *arbitrary* shape can be reduced. For example, one may seek an equivalent distribution of ellipsoidal inhomogeinities that represent defects of irregular shape from the standpoint of the elastic properties (we note that this problem is of fundamental interest for broader material science applications that are not limited to metals). The challenge is to distinguish the *"irregularity factors"* of primary importance that produce substantial effects on the overall elasticity/property, from factors of minor importance, and to develop sufficiently simple *quantitative characterization* of these primary factors. Our research will combine the theoretical methods based on bounding approaches (such as Hill's comparison theorem) and computational studies.

The outcome of this research will be twofold: 1) an independent method to determine the change in bulk material properties due to damage – this information will be used in the vibration and ultrasonic SHM methodologies; and 2) research to establish direct connections between measured or inferred cross-property connection parameters and damage in materials – this would add a fundamentally new methodology to SHM.

c) High frequency Nonlinear Ultrasonic SHM

During the past decade, considerable progress has been achieved in utilizing elastic wave propagation for SHM (Lemistre *et al*., (2000), Guirgiutiu *et al*., (2003), Ihn and Chang (2004), Raghavan and Cesnik, (2005)). However, detectability of structural damage is frequency dependent (Bray and Stanley, 1997). On one hand, very small defects may not be resolved adequately if relatively low frequencies are employed. On the other hand, high frequency ultrasonic waves may attenuate rapidly, imposing limitations on the effective detection range.

One approach to address the small-scale damage issue is to explore the nonlinear nature of the structural damage at high frequencies. Correlation between acoustic nonlinearity and material damage has been known for over forty years (Beyer, 1974). Prior work on this subject was contributed by Hikata *et al*., (1966) Breazile (1984), Cantrell and Yost (2001), Nagy (1998), Van Den Abeele *et al*. (2001), Kim *et al*., (2004). Recent results on the use of the nonlinear ultrasonic approach for assessment of degradation in aerospace materials were reported by Frouin *et al*. (2000), Na *et al*. (2003), Donskoy *et al*., (2006), Zagrai *et al*. (2006a). Although there is a considerable volume of work on application of the principles of the nonlinear wave propagation in NDE, realization of this methodology in the SHM context has been limited (Zagrai *et al*. 2006b). The development in this field is currently dominated by the nonlinear SHM methodologies exploring structural dynamics at relatively low frequencies (Doebling et al., 1996; Todd, *et al*., 2004, Adams and Nataraju, 2002, Epureanu *et al*., 2005).

A harmonic acoustic wave propagating in a nonlinear medium is distorted, leading to generation of multiple harmonics and nonlinear interaction with structural inhomogeneities. A one-dimensional wave equation in the second order nonlinear approximation shows that displacement of the elastic wave is dependent not only on linear elastic properties of the medium, i.e. sound speed $c_0 = (E / \rho)^{1/2}$, where E is an elastic modulus and ρ is a mass density, but also on a nonlinear parameter β of the medium:

$$\frac{\partial^2 u}{\partial t^2} - c_0^2 \cdot \frac{\partial^2 u}{\partial x^2} = -2\beta c_0^2 \cdot \frac{\partial u}{\partial x}\frac{\partial^2 u}{\partial x^2}$$

The parameter β can be physically attributed to the nonlinear processes at micro, meso, and macro scales, (Van Den Abeele *et al*., 1997, 2000). Therefore, *measurements of β could potentially provide information on the nonlinear processes associated with damage.*

Although low frequency methods may yield a cost effective solution for assessment of overall structural health, their damage localization capabilities and sensitivity to small-scale damage are limited. Therefore, we propose to couple the nonlinear ultrasonics technique with the low frequency, global nonlinear vibration methods to obtain a cumulative, multi-scale and complete picture of the structural health. We will develop a high frequency SHM technique that is based on the nonlinear interaction of the propagating elastic waves at the site of an incipient damage. The technique utilizes a complex multi-component excitation signal facilitating the amplitude-phase modulation of the elastic wave. The result of the quadratic nonlinear interaction of the elastic waves due to damage-induced structural nonlinearity is manifested at the combination (modulation) frequencies, $\omega_{\pm}=\omega_0\pm\omega_1$, as presented in Figure 3. These spectral components comprise the nonlinear ultrasonic signal propagating through the damaged structure.

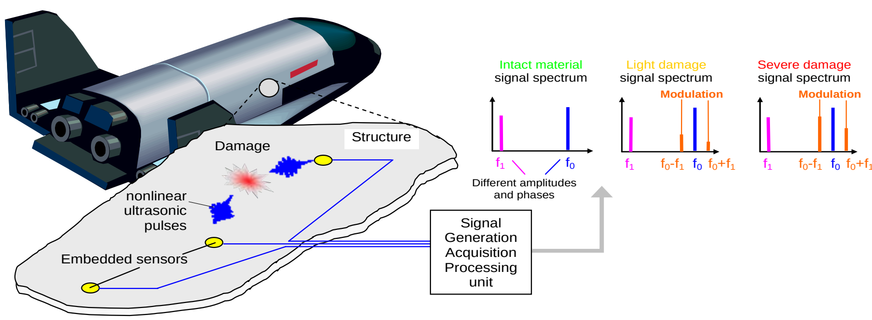

Figure 3 - The embedded nonlinear ultrasonics concept.

We plan to utilize general amplitude-phase modulation using the proposed embedded SHM methodology. We will focus on aerospace thin-walled structures that still await detailed investigation of the fatigue-induced nonlinear ultrasonic response. The challenge of the proposed research efforts is realization of the nonlinear ultrasonics in the embedded format. This will necessitate development of new thin wafer embeddable sensors/transducers, studying detrimental influences of equipment nonlinearities, and investigation of the effect of fatigue damage on nonlinear guided wave propagation in thin-walled structures. Our broader goal includes utilizing results of nonlinear ultrasonic measurements in connection with electrical conductivity assessment and nonlinear vibration diagnostics for development of the proposed multi-scale SHM approach. Availability of real-time nonlinear ultrasonic data on structural deterioration will open new opportunities in prognosis and will facilitate improvements in structural maintenance and safety.

d) <u>Self- Healing Systems (SHS) of Materials</u>

The idea of engineering synthetic substances that are capable of self-repairing and adaptation to changing environments came to the scientific world many years ago. The concepts of structural polymeric materials with the ability to autonomically heal cracks have been developed only recently (see, for example, White et al., 2001). According to these concepts, the material incorporates a microencapsulated healing agent that is released upon crack intrusion. Polymerization of the healing agent is then triggered by contact with an embedded catalyst, bonding the crack face. This concept has disadvantages, such as high concentration of embedded capsules, weaker mechanical properties of the new material, and non-compatibility of healing and matrix materials.

Another interesting self-healing system utilizes the electrohydrodynamic coagulation ability of particles to close a defect in materials (see, for example, Trau et al., 1997). When a defect occurs in the insulating coating, the metal underneath is exposed to create high current density at the damaged site, causing colloidal particles to coagulate around the defect. The disadvantage of this technology is related to difficulties to detect the cracks and damages at the initial stages. Currently no technology is known for self-healing in metals and metal-based composites. The difficulties are high temperature and pressure during manufacturing processes of metallic parts (casting, forging, rolling, stamping, etc.).

The research team will target a revolutionary technology for self-healing concepts in metals, alloys and plastic composites, which can lead to significantly increased safety of aerospace vehicles and structures. Several concepts will be developed and realized for self healing in metals. In one concept, self-healing is assumed to be achieved by incorporating a microencapsulated healing agent of complex composition and a catalyst within the metal matrix composite manufactured via a powder metallurgy process. Microcapsules will be filled by the same bonding agent used in sintering processes. A propagating crack will burst the microcapsules. The healing agent released into the crack will contact the catalyst particles, bonding the crack face.

Bakhtiyarov and Overfelt (1997-2002) have demonstrated an exothermic character of most two-part binding systems. These findings will be utilized in another self-healing concept of metals, alloys and metal-based composites. In terms of the candidate fillers, a self-healing system (SHS) of exothermic reactions, such as Ti and C for example, would be initiated by the heat generated from the approaching crack and the compound formed would fill the cavity and thus cure the crack and avoid failure in the system. The presence of microcapsules containing the SHS components would enhance toughness in the material, with the interfaces generated, and the new alloy (compound) formation would be the requisite cure to the crack.

For thin coatings the research team will develop chemically, thermally and mechanically stable conducting coating materials capable of detecting the damaged (cracked) area in the material's surface. The signal from the damage will be sent to the external field generator (thermal, electrical, magnetic, etc.) to initiate a self-healing process by coalescing field active particles (initially introduced to the matrix) around the defect.

The research team will develop new classes of nanoencapsulated systems for binders. The healing agent and the catalyst will be encapsulated within double-walled nanotubes. By applying the catalytic chemical vapor deposition process, the core and the annular spaces of the double-walled nanotubes will be filled by the healing agent and the catalyst, respectively. A crack within the composite matrix will rupture embedded nanotubes. The healing agent and the catalyst will be released into the crack via capillary effects. Upon the contact of the healing agent with the catalyst, a polymerization will be generated, and the crack will be filled. The advantages of using double-walled nanotubes are: (i) a nanosizing of the capsules produces an increase in surface area more than 1,000 times compared to spherical microcapsules at the same mass concentration; (ii) the material of the nanotubes can be selected to be compatible with both curing agents and the matrix composite, and this will eliminate undesirable interface effects; (iii) the healing agent and the catalyst will be released simultaneously; (iv) the embedded double-walled nanotubes will increase thermal, mechanical and chemical stability of the matrix composite; (v) the continuous shape of the capsules will increase probability of their being ruptured by the propagated crack.

e) Integration of multi-scale SHM and SHS methodologies

The three SHM techniques discussed in this proposal will be closely integrated in two important ways. First, the techniques will yield information concerning damage in the internal structure at three different scales: 1) vibration-based SHM to determine the sizes and locations of macroscopic fatigue cracks, 2) electrical conductivity measurements to determine changes in bulk material properties, and 3) acoustic wave propagation to determine microscopic crack densities. This information will be integrated to form a complete multi-scale model of the structure in which the effects of damage at any scale may be extracted. One popular approach which will be investigated for this purpose is the use of fractal mathematics. Fractals are functions which describe topographies with great detail at all length scales, and could be used to approximate multi-scale damage effects. Second, because the vibration-based SHM measurements contain combined information on the structure's material and joint damage, these aspects of the structure must be separated to yield a joint damage model which is distinct from the material damage model. Here, the additional information on the material damage obtained through the other measurement techniques will help to separate out the effects of the joints from the material damage.

For SHS/SHM integration, including experimental work, the proposed SHM systems (nonlinear ultrasonics, four-point co-linear probe resistivity, etc.) will detect defects by continuous scanning of the coated surfaces. The signals from detection systems will initiate activation of the self-repairing particles and appropriate local environmental conditions, such as temperature, pressure, humidity, etc. One of the challenges of the self-repairing materials technology is to embed micro sensors into the developed matrix so one can predict failure with confidence. Usually, sensors are positioned randomly, organizing themselves into a network with no maintenance. However, in order to maintain the strength and other properties of the self healing material, sensors must be embedded in desired locations where the probability of failure is high. Therefore, a Rapid Prototyping (3D Printing) technology will be the most suitable manufacturing technique to introduce the "healing" agents (capsules) into the matrix material and imbed micro sensors during the 3D printing process. The first test samples are suggested to be manufactured using a Rapid Prototyping technology. A rapid prototyping machine builds up the prototype model from a series of cross sections. The layers are glued together automatically to produce the desired shape. This technology is applicable for a wide variety of materials (polymers, thermoplastics metals, ceramic powders, etc.). High temperature and high pressure conditions are not required.

f) Work Plan and Preparation for Follow-on Research

During year 1 the four technical project areas described in the preceding sections will be pursued by the investigators identified in Section 11b (p15). Timelines and milestones are listed in Table 1, pg. 16. The objective will be to conduct theoretical, modeling, and simulation research in order to identify and pursue the most promising specific lines of attack in each of the individual research areas and in the methodology for integration of the SHM and SHS approaches. The second task of year 1 will be to hold regular group discussions to develop integration strategy of individual research areas into the overall multi-scale SHM/SHS strategy and to design an experiment that is sufficiently broad based to enable the integrated multi-scale methodology to be validated.

During year 2 we will continue the work on methodology development, with increased focus on integration of the individual research areas into the overall SHM/SHS methodology. We plan to set up and conduct the experimental research planned in year 1, with modifications as needed, depending on outcomes.

During year 3 we plan to complete sufficient experimental work to enable individual and integrated methodologies to be validated. It is anticipated that additional experimental research will need to be done in follow-on projects. It is also anticipated that follow-on research in the theoretical methodologies and in structural self-healing will be needed, depending on the outcomes of the proposed research.

A further objective in year 3 will be to prepare for follow-on research by developing a strategy for "damage prognosis" of aerospace structures. Damage prognosis is viewed by Farrar and Lieven (2007) as the next "grand challenge" problem in the SHM and structural life prediction arena. This involves use of SHM measurements and methodologies, combined with dynamic models of damage evolution and models of the future environment to which the structure will be subjected in order to predict useful life of a structure. The accomplishment of damage prognosis for complex aerospace structures will likely involve use of large nonlinear finite element models, reduced order modeling of these models, novel sensing and signal processing, hardware in the loop simulation to analyze critical components, and development of the dynamic damage models needed for prognosis. The NASA EPSCoR research team, along with collaborators at NASA and LANL, will be well prepared to attack such problems once the research proposed here is initiated.

5. Impact of the proposed work to the state of knowledge in the field

- Methodology incorporating nonlinear crack and joint modeling to complement material damage modeling will be a significant advance in the state of the art. For many aerospace structures the possibility of joint/connection damage cannot be ignored.
- Nonlinear ultrasonic SHM using embedded sensors promises to be an excellent method for local, small-scale damage detection. Accompanying advances in applications of signal processing to detect small nonlinear effects in the acoustic responses will be valuable.
- The use of electrical conductivity measurements and cross-property connections to provide more information is a new addition to the field of SHM. Furthermore, in the future the methods may lead to new SHM approaches, as yet unknown, whereby electrical conductivity measurements and/or cross-property connection parameters can be related directly to structural damage.
- The possibility to develop self-healing materials in such a way that failure is prevented and material toughness is maintained would be of significant value in aerospace applications. It is anticipated that the proposed research will provide the seeds for significant future work in self-healing materials.
- The proposed framework, in which multi-scale damage and combined joint/material damage are considered through integration of the aforementioned methodologies, will be valuable in the future, as SHM matures to the point where the development of real time, self-monitoring and self-healing materials becomes practical.

6. Existing Research

Baseline information about current research in proposed research areas: Current research at NMSU in the proposed research area includes fundamental studies of micromechanics and of cross-property connections in materials with defects. The application of this work to SHM is new. Basic studies of nonlinear vibrations and structural dynamics, including reduced order modeling and simulation, is a research focus area at NMSU. Application to model-based SHM has been done, but this work has not been extensive. Currently, NMT has active research programs on materials characterization and development of effective binding agents, relevant to the proposed research in self-healing systems. The Laboratory for Intelligent Systems and Structures (LISS) at NMT focuses on research in structural health monitoring and intelligent mechatronic systems. Current research aims to develop new SHM techniques and innovative sensors for aerospace vehicle monitoring and embedded diagnostics via nonlinear ultrasonics.

New Mexico NASA EPSCoR was established in May of 2007. There is no current research in New Mexico being funded under New Mexico NASA EPSCoR.

7. Relevance to NASA and Jurisdiction

The proposed research is directly applicable to the following research programs at NASA Mission Directorates:

ARMD: Aircraft Aging and Durability Detection, Aircraft Aging and Durability Mitigation, Aircraft Aging and Durability Prediction, Airframe Health Management, Optical Instrumentation and NDE Technology, Structures and Materials

ESMD: Advanced Materials

The proposed research is directly relevant to the "Advanced Materials and Sensors for Space Exploration" program that supports NASA's vision for Space Exploration. The program initiated at NASA MSFC includes the development of various self healing materials (metals, polymers, nanocomposites, etc.) for use in spacecraft, propulsion systems, cosmic radiation shielding, etc. during the missions to Moon and Mars. The areas of interest of this program also include development of sensors for structural health monitoring to support space exploration.

In addition, twelve research programs at four NASA Centers (Langley, Marshall, Glenn, and Dryden) have been identified as directly related to the proposed research.

Relevance to New Mexico's goals and research, structure and technology priorities: In 2003 the State of New Mexico determined it was of critical importance to establish an aerospace engineering program in the state to enhance future economic development and for academic and research competitiveness. Concurrently, the Department of Higher Education determined that all three research universities would be involved in this program at the undergraduate and/or graduate levels. For this purpose state funds were recently appropriated at the level of $486,000 in recurring funds, to be used by NMT and NMSU to develop an undergraduate AE degree program at NMSU (BS degree approved) and an undergraduate option in AE at NMT. The first AE courses were offered during the 2006/2007 academic year. Graduate AE degree programs (MS and PhD), are planned starting in 2008, and will involve a collaboration of the three New Mexico research universities, with distance education for course delivery. New Mexico Space Grant Consortium has been a partner is funding the distance education course delivery. The proposed research program will be critical in providing a platform from which to launch the graduate programs in aerospace engineering.

TAC input used in selecting the proposed research: All members of the New Mexico Technical Advisory Committee (TAC) were contacted by the New Mexico EPSCoR Director and invited to participate in the process of selecting the proposals to go forward to NASA. A 7 member sub-group of the New Mexico EPSCoR TAC reviewed seventeen pre-proposals submitted after a statewide request was released on June 1, 2007. Four pre-proposal were selected to prepare full proposals. This proposal was selected by the TAC sub-group to submit to NASA on June 26th, 2007.

8. Partnerships/sustainability

The proposed research is a collaboration between New Mexico Tech and New Mexico State University. Future collaboration with University of New Mexico researchers, especially in graduate education and associated research, is expected as the proposed program develops and is extended through funding from other sources. During the period of performance the research team will collaborate with the SHM team led by Dr. Charles Farrar at Los Alamos National Lab. The joint NMSU/NMT/LANL research programs will enhance the overall stature of SHM/SHS and related research in the state of New Mexico.

Energy Reclamation LLC, a Tulsa (OK) based company, will participate in the proposed project. A special interest of this company is self healing phenomena in metallic composites. The company has committed $285,000 in-kind cost share for the project. Energy reclamation LLC also will help in patenting and commercialization of the new developments in aerospace and other industries.

Plan and schedule for achieving national research competitiveness: National research competitiveness will require publication of research results in top journals (with attendant citations), production of PhD graduates that can compete with graduates of top universities for research and academic positions, and the ability to compete with all comers in the competitive federal funding programs (e.g., NSF, DoD). The following plans will move us to national competitiveness:

- Develop a state wide Research Center in SHM, SHS and related areas such as verification and validation (V&V), modeling and simulation, sensing, and damage prognosis. NMSU, NMT, and LANL have agreed in principle to launch this initiative; Sandia National Labs and UNM are likely partners, as are the relevant NASA Centers. The plan will be to organize this Center during years 1-2 of the EPSCoR project, and to be completing joint research projects and competing for funds by years 2-3. A main goal of this collaboration will be to establish New Mexico as a national leader in the next grand challenge of SHM: damage prognosis.
- Use the SHM/SHS research area and the aforementioned Research Center as a primary focus for development of a NSF Integrative Graduate Education and Research Traineeship (IGERT) program in the general area of interdisciplinary modeling, simulation, and high performance computing. The objective of this program would be to educate PhD students in diverse technical areas, including depth in HPC, enabling them to function broadly and deeply in the research arena. Design of the curriculum and definition of the research focus areas (of which SHM/SHS would be one of several) will require care, and the goal would be to prepare for this IGERT grant during year 1 and to propose during years 2-3.

9. NASA interactions

A team member Dr. Bakhtiyarov previously interacted and collaborated with NASA scientists and engineers at Marshall Space flight Center (Huntsville, AL) on two projects related to the proposed research: (i) NASA's Office of Life and Microgravity Sciences and Applications under Cooperative Agreement No. NCC8-128, 1995-2000, and (ii) NASA's Space Product Development under Cooperative Agreement No. NCC8-240, 2000-2005. The research and development results on characterization and processing of aerospace structural materials and binding agents are published (more than 100 scientific papers) with NASA collaborators in refereed scholarly journals (including NASA Tech Briefs) and conference proceedings. Currently, Dr. Bakhtiyarov interacts with researchers and scientists from Center for Microgravity and Materials Research, Huntsville, AL.

<u>How future collaborations of research team with Center/Mission personnel will be fostered</u>: In the area of nonlinear ultrasonics, NMT researchers have been interacting with Dr. George Baaklini, a Director of Optical Instrumentation & NDE Branch at NASA Glenn Center. To better fit within the branch research mission, for this project Dr. Baaklini recommended close collaboration with Dr. John Lekki – an expert in integrated vehicle monitoring. Interaction with Dr. Lekki has led to the concept of the future collaboration in which the proposed SHM methodologies will complement existing NASA Glenn efforts in SHM of aerospace systems.

Names and titles of NASA Researchers with whom proposers will collaborate:

Dr. Benjamin Penn, Polymer Scientist, NASA Marshall Space Flight Center, Org. EV 43 – Advanced Materials and Sensors for Space Exploration, Huntsville, AL (256-544-7809). Area of interests: self-healing materials and sensors for space exploration.

Dr. Shandor (Alex) L. Lehoczky, Technical Specialist, Microgravity Science and Application Department, SD 46, NASA Marshall Space Flight Center, Huntsville, AL 35812 (256-544-7758). Areas of interest: Self Healing Materials, Solid State Physics, Materials Science, Properties of Materials, Electronics Materials, Microgravity.

Dr. John Lekki, Optical Systems Research Engine,NASA Glenn Research Center, MS 77-121000 Brookpark Rd., Brook Park, Ohio 44135 (216)433-5650. Areas of interest: optical systems, structural health monitoring

10. Diversity and Outreach

NMSU is a Hispanic serving institution with a 54% minority student body. Female enrollment in engineering is low. In order to attract underrepresented groups, we plan to involve the Hispanic, Native American, Black, and Women Engineering programs at NMSU and at NMT in order to attract minority and female students to the proposed research and supporting academic programs. Students with disabilities will be recruited through the NMSU RASEM (Regional Alliance for Science, Engineering, and Mathematics) program, which has a strong track record recruiting disabled students. Other state wide programs operated by the Colleges of Engineering at NMSU and NMT will provide a wide geographical outreach in support of this program.

11. Management and Evaluation

a) Personnel

- Principal Investigator - Patricia C. Hynes, Director of the New Mexico NASA EPSCoR Program and Director of New Mexico Space Grant Consortium.
- Co-Investigator, Sayavur Bakhtiarov, ME Chair, New Mexico Tech
- Co-Investigator, Thomas Burton, ME Head and Professor, NMSU
- Co-Investigator, Eric Butcher, Assoc. Prof. of ME, NMSU
- Co-Investigator, Igor Sevostianov, Assoc. Prof. of ME, NMSU
- Co-Investigator, Andrei Zagrai, Asst. Prof. of ME, New Mexico Tech
- Graduate Research Assistants to be identified
- Graduate Students supported by this research effort will be U.S. citizens in an effort to build the technical workforce prepared to work for NASA and its contractors. New Mexico NASA EPSCoR is committed to supporting diversity and will encourage female, minorities and persons with disabilities to actively participate in the program.

NOTE: Drs. Sevostianov and Zagrai are US Residents and will soon be eligible to apply for US Citizenship. Dr. Sevostianov is in a tenure faculty position and NMSU and plans to reside in New Mexico. Dr. Zagrai is in a tenure faculty position at New Mexico Tech and plans to reside in New Mexico.

b) Research Program Management

New Mexico EPSCoR will be managed through the New Mexico EPSCoR/Space Grant lead office at New Mexico State University. Dr. Patricia C. Hynes, Director of New Mexico Space Grant, will also serve as the Director of the New Mexico NASA EPSCoR and will be responsible for the day-to-day management of the NASA EPSCoR program, including interactions among collaborating institutions, NASA Field Centers, and space and aerospace related industry. The NM EPSCoR Director will work with the State of New Mexico EPSCoR Committee to facilitate interactions and coordination between these organizations. The NM EPSCoR Director will work closely with the Technical Advisory Committee (TAC) to align our research focus to meet NASA and New Mexico research priorities. The EPSCoR office will be responsible for contract requirements including budgeting, tracking and reporting requirements. NASA EPSCoR office will also organize annual meetings for New Mexico faculty to facilitate research collaborations among colleges and universities.

The technical aspects of the proposed research will be performed by the five co-PI's, with participation as follows (lead investigators underlined will manage the listed technical areas):

- Vibration based SHM: <u>Butcher</u>, Burton, Zagrai
- Cross-property connections: <u>Sevostianov</u>, Butcher, Bakhtiarov
- Nonlinear ultrasonic SHM: <u>Zagrai</u>, Burton, Butcher
- Self-healing systems (SHS): <u>Bakhtiarov</u>, Zagrai, Sevostianov
- Integration of Multi-Scale SHM/SHS methodologies: <u>Burton</u>, Bakhtiarov, Butcher, Sevostianov, Zagrai

c) Program Evaluation

New Mexico EPSCoR Director Dr. Patricia Hynes has conducted extensive activities in educational assessment. She will design and implement the evaluation plan. Evaluation data will be collected from researchers each year as part of their report to NASA EPSCoR. The evaluation will allow us to monitor our progress and document benchmarks toward achievement of program goals and objectives.

The evaluation will be both formative and summative. Formative evaluation will include an annual assessment of the proposed research metrics. Formative evaluation results will be brought to the NASA EPSCoR Technical Advisory Committee (TAC) for ways to enhance program success. NASA collaborators will be involved in annual progress evaluations. Summative evaluation will include a comparison of pre-award and post-award data analysis.

Research faculty will involve undergraduate and graduate students in their research. This will not only contribute to workforce development in NASA research areas but encourage student retention. Students receiving $5,000 or more in support will be tracked through first employment. We will track students through the university registration systems, confirming students are still enrolled and succeeding in their STEM degrees.

The Milestones and Timeline for New Mexico EPSCoR are: Table 1

Milestone	**Year 1**	**Year 2**	**Year 3**
Basic research in four areas	***********	***********	***********
Design validation experiment	***********	**	
Conduct validation experiment		***********	***********
Integrated multi-scale methodology development	**	***********	***********
Methodology validation		*****	***********
Deliverable: validated methodology			***********
NASA panel evaluations	**	**	***********
Organize statewide/NASA collaboration	*****	****	
Statewide/NASA joint research		***********	***********
IGERT proposal	***********	***********	***********

<u>Milestones and timelines</u>: The milestones and timelines for the first two Objectives listed in Section 2 have been summarized in Table 1: conduct theoretical modeling and simulation research and determine integration strategies to enable experiment design. For the third Objective the three-year milestones (minimum of six students) will include the number of graduate and undergraduate students working in the proposed research area at NMSU and at NMT and the number of interns and co-op students accepting assignments with NASA and other collaborators in the proposed research area. The impact of the project on K-12 students will be assessed but will be difficult to quantify. For the fourth Objective, a key milestone will be completion of an IGERT proposal that will be based on the technical areas in this proposal (as well as others). In addition, proposals to other competitive programs at NSF, DoD, etc. will

constitute important milestones. It is anticipated that realization of these milestones will be in years 2 and 3. Also relevant to the fourth Objective will be journal publication with PhD student involvement. An approximate milestone will be to generate at least 10 journal publications with graduate student involvement within one year of completion of the proposed research. The primary milestone for the fifth Objective involves organizing the state-wide Research Center among NMSU, NMT, UNM, LANL, and Sandia, as described in Section 8 (Plan for Achieving National Research Competitiveness p13). The milestone is to develop and pursue joint research projects among the collaborators by year 2. Co-PI T. Burton and Dr. Charles Farrar (LANL) have agreed in principle to develop this research collaboration in areas of and related to the proposed research.

d) Tracking of Program Progress:

The progress and potential towards achieving self-sufficiency beyond the award period of the research capabilities developed under this grant are indicated in the timeline : the assessment metrics will be the primary means for this assessment.

- The potential for the proposed research area to continue to grow in importance in aerospace fields in the future: an assessment of the stated potential would require significant input from the aerospace industry (including AIA and AIAA), from NASA, from academia, and others. The number, type, and deployment of new SHM/SHS devices and patents would be relevant, as would the number of published journal articles over time. We are not equipped to perform such an assessment.

e) Continuity

Through their participation in this research, students are prepared for employment in disciplines needed to achieve NASA's mission and strategic goals. We will encourage participation from New Mexico students enrolled in other NASA sponsored programs, including NMSGC students, and USRP, GSRP, or ESMD programs. Through this research and internships and fellowships students become participants in NASA's Vision for Space Exploration and NASA's science and aeronautics research, and acquire sufficient mastery of knowledge for employment with NASA and its contractors.

EPSCoR funding provides researchers equipment and material necessary to advance this research area in the state. This funding supports faculty publications, increasing their eligibility for non-EPSCoR funding, and bringing the research team to a level of national competitiveness.

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EDUCATION

DSc in Mechanical Engineering, Birmingham University, UK, 1992
PhD in Mechanical Engineering, Institute of Thermophysics, Russia, 1978
MS in Mechanical Engineering, Azerbaijan State Oil Academy, Baku, 1974
BS in Petroleum Engineering, Azerbaijan Institute of Oil and Chemistry, Baku, 1972

PROFESSIONAL EXPERIENCE

1/05 – present Head, Associate Professor, Department of Mechanical Engineering, New Mexico Institute of Mining and Technology, Socorro, New Mexico, 87801
2/95 - 1/05 Research Professor, Space Power Institute, Auburn University, Alabama 36830
5/78 - 2/95 Head, Full Professor, Azerbaijan State Oil Academy, Baku, Azerbaijan 370010
8/74 – 1/75 Research Assistant Professor, Academy of Sciences, Baku, Azerbaijan 370601

Relevant Publication

S. I. Bakhtiyarov and R. A. Overfelt, "Improved Sand-Compaction Method for Lost-Foam Metal Casting", *NASA Tech Brief*, **MFS-31679-1** (2006)

N. Khidasheli, E. Kutelia, S. Bakhtiyarov, G. Beradze and K. Demirkiran, 2006, "Thermo-Mechanical and Isothermal Treatments Influence on the Wear of ADI during Dry Friction", *Georgian Engineering News***,** **4**, 25-34 (2006)

S. I. Bakhtiyarov, "Numerical Simulations and Experimental Study of Liquid Metal Flow around Sand Core", *Journal of Fluids Engineering***,** **128**, 541-547 (2006)

E. R. Kutelia, O. O. Tsurtsumia, B. G. Eristavi, H. Adanir and S. I. Bakhtiyarov, "Structure and Elemental Distribution in Beilby Layer on the Surface of Fe-Cr-Al-La Alloy", *Journal on Engineering and Technology,* **1**(4), 61-71 (2006)

S. I. Bakhtiyarov, M. Dupac, R. A. Overfelt and S. G. Teodorescu, "On Electrical Conductivity Measurements of Molten Metals by Inductive Technique", *Journal of Fluids Engineering,* **26,** 468-470 (2004)

Other Significant Publications

S. I. Bakhtiyarov and R. A. Overfelt, "Improved Probe for Evaluating Compaction of Mold Sand", *NASA Tech Brief*, **MFS-31678-1 (**2006)

S. I. Bakhtiyarov, O. T. Inal, B. Guo, R. A. Overfelt, "A New Image Analysis Method for Shape Prediction of a Levitated Aspherical Droplet", *Journal on Engineering and Technology,* **1**(1), 67-73 (2005)

S. I. Bakhtiyarov, R. A. Overfelt and D. Wang, "Thermophysical Property Measurements on Mold Materials: Thermal Expansion and Density", *International Journal of Thermophysics,* **26**(1), 141-149 (2005)

S. I. Bakhtiyarov and R. A. Overfelt, "Effect of Porosity and Metallic Insertions on Electrical Resistivity of A2011 Aluminum Alloy", *Materials Science and Technology*, **20**, 790-794 (2004)

A. J. Meir, P. G. Schmidt, S. I. Bakhtiyarov and R. A. Overfelt, "Numerical Simulation of Steady Liquid-Metal Flow in the Presence of a Static Magnetic Field", Transaction of the ASME, *Journal of Applied Mechanics***,** **71**, 1-10 (2004)

S. I. Bakhtiyarov and R. A. Overfelt, "Thermophysical Properties Measurements Using Electromagnetic Levitation under Microgravity: Electrical Resistivity", *International Symposium on Physical Science in Space: Spacebound,* Proceedings, Toronto, Canada (2004)

Awards and recognition

2006 Best Paper Award of the South American Electrochemical Society (SIBAE)
2003 ASME International Mechanical Engineering Congress and Exposition Award
2001 Best Paper Award of the American Foundry Society
2001 International Medal for Scientific Excellence
1996 Granted permanent residency in the US as a Scientist of Extraordinary Ability
1987 USSR National Economy Achievements Award
1982 Recipient of the Oil Academy's Outstanding Young Faculty Award
1972 Outstanding Student Doctoral Award of the USSR Ministry of Education

Other relevant qualifications/activities (recent)

- Topic co-organizer of "Advances in Materials Processing Science" Symposium, ASME International Mechanical Engineering Congress and Exposition, Seattle, WA, 2007
- Topical co-organizer of "Rheology and Fluid Mechanics of Nonlinear Materials" Symposium, ASME International Mechanical Engineering Congress and Exposition, Seattle, WA, 2007
- Symposium coordinator of "Flows in Manufacturing Processes" Symposium, ASME Joint U.S.-European Fluids Engineering Summer Meeting, Miami, FL, 2006
- Topic co-organizer of "Advances in Materials Processing Science" Symposium, ASME International Mechanical Engineering Congress and Exposition, Chicago, IL, 2006
- Topical co-organizer of "Rheology and Fluid Mechanics of Nonlinear Materials" Symposium, ASME International Mechanical Engineering Congress and Exposition, Chicago, IL, 2006
- Editor in Chief of the "International Journal of Manufacturing Science and Technology" (IJMS&T)
- Editor in Chief of the International Journal of Mechanics and Solids (IJM&S)
- Editorial Board Member of Journal of Mathematics Applied in Science and Technology (MAST)
- Editorial Board Member of International Journal of Applied Engineering Research (IJAER)
- Editorial Board Member of International Journal of Dynamics of Fluids (IJDF)
- Editorial Board Member of Far-East Journal of Mathematics (FEJM)
- Member of Professional Societies:
    - Society of Petroleum Engineers (SPE)
    - The British Society of Rheology (BSR)
    - American Society of Mechanical Engineers (ASME)
    - American Foundry Society (AFS)

BIOGRAPHICAL SKETCH - THOMAS D. BURTON

Department Head of Mechanical and Aerospace Engineering
New Mexico State University

EDUCATION

PhD in Mechanical Engineering and Applied Mechanics, University of Pennsylvania, 1976
MS in Mechanical Engineering and Applied Mechanics, University of Pennsylvania, 1972
BS in Engineering (Major: Aero), California Institute of Technology, 1969

PROFESSIONAL EXPERIENCE

6/05 – present	Head, Department of Mechanical Engineering, New Mexico State University, Las Cruces, New Mexico, 88003-8001
7/95-6/05	Chair (7/95 – 8/04) and Professor, Department of Mechanical Engineering, Texas Tech University, Lubbock, Texas 79409-1021.
1997-present	Affiliate, Los Alamos National Laboratory, Engineering Sciences and Applications, Los Alamos, NM
8/91-10/92	Acting Department Chair, Mechanical and Materials Engineering Department, Washington State University, Pullman, WA 99164-2920.
1977-1988	Professor (1988-1995), Associate Professor (1982-88), Assistant Professor (1977-82), Department of Mechanical Engineering, Washington State University, Pullman, WA.
1969-1977	Engineer, General Electric Co., Missile and Space Division, Valley Forge, PA: 1975-77: Intelligence Programs Group, Space Sciences Lab; 1969-75: Flight Dynamics Group, Re-Entry and Environmental Systems Division.

Relevant Publications

1. J-L Ding, J Pazhouh, SB Lin and TD Burton, "Damage Characterization by Vibration Test," *Scripta Metallurgica et Materialia*, **30**(7), 839-844 (1994)
2. TD Burton, C.R. Farrar, and S.W. Doebling, "Two Methods for Model Updating Using Damage Ritz Vectors," Proc. IMAC XVI, pp. 973-979, Santa Barbara (1998).
3. TD Burton and W Rhee, "On the Reduction of Nonlinear Structural Dynamics Models," *Journal of Vibration and Control*; **6**(4), pp. 531-556 (2000).
4. TD Burton, F. M. Hemez and W. Rhee, "A Combined Model Reduction/SVD Approach to Nonlinear Model Updating," Proc. IMAC XVIII, pp. 116-123, San Antonio (2000).
5. J. Kim and TD Burton, "Reduction of Nonlinear Structural Models Having Non-Smooth Nonlinearities, Proc. IMAC XX, pp. 324-330, Los Angeles, CA (2002).
6. J Kim and TD Burton, "Reduction of Structural Dynamics Models Having Nonlinear Damping," ASME 2003 DETC, 19th Biennial Conf. On Vibration and Noise, September 2-6, Chicago, IL (2003).
7. TD Burton, "Numerical Calculation of Nonlinear Normal Modes in Structural Systems," *Nonlinear Dynamics*, to appear (2007).

8. N Kumar and TD Burton, “Use of Random Excitation to develop POD based reduced order models for nonlinear structural dynamics,” Proc. ASME IDETC, Paper DETC2007/VIB-35539, Las Vegas, NV, September 4-7 (2007)

Other publications

1. T.D. Burton, Introduction to Dynamic Systems Analysis, McGraw-Hill (1994).
2. T.D. Burton and M.N. Hamdan, “On the Calculation of Nonlinear Normal Modes in Continuous Systems,” *Journal of Sound and Vibration*, **197**(1), pp.117-130 (1996).
3. P Meekangvan, AA Barhorst, TD Burton, S Chatterjee, and L Schovanec, “Nonlinear Dynamical Model and Response of Avian Cranial Kinesis,” *J. Theoretical Biology*, **240**, 32-47 (2006).

Other relevant qualifications/activities (recent)

NASA Workforce Development Workshop participant; sponsored by NASA ESMD; “PartneringStrategies for Educating and Motivating the Next Generation of Aerospace Scientists and Engineers,” Washington DC, June 1, 2006.

Participant, 2007 National Science Symposium for Engineers and Scientists, Santa Fe, NM: Purpose of Symposium: Improve K-12 Science Education in US.

Panel Organizer and Moderator, International Symposium for Personal Spaceflight (ISPS 2005, 2006), Las Cruces, NM

Member (2000-2006), external review panels for ASC predictive simulation programs in Mechanics (Sandia National Lab and Los Alamos National Lab)

Member, Editorial Board, *Journal of Vibration and Control*

Guest editor, *Nonlinear Dynamics* (2 special issues)

Responsible for all aspects of development of Aerospace Engineering degree programs at NMSU, including management of line item state funding (2005 – present)

PI on AFOSR grant ($251,975 Predictive Dynamic Simulation of Structures with Non-Smooth Nonlinearities; 2002 – 2005).

NMSU Technical Lead (PI is Stanford University): Army High Performance Computing Research Center (AHPCRC); NMSU Share = $750,000 per year (start date: 6/2007; duration: 5-10 Years)

National President, Pi Tau Sigma (ME Honorary Society), 2004-2007.

BIOGRAPHICAL SKETCH - ERIC A. BUTCHER

Education

Ph.D. (Mechanical Engineering), 1997, Auburn University, Auburn, AL.
M.S. (Mechanical Engineering), 1995, Auburn University, Auburn, AL.
B.S. (Engineering Physics) with distinction, 1993, University of Oklahoma, Norman
B.M.A., 1991, University of Oklahoma, Norman

Professional Experience

2007: Associate Professor, Mechanical and Aerospace Engineering Dept., New Mexico State University
2003-2006: Associate Professor, Mechanical Engineering Dept., University of Alaska Fairbanks (tenured)
1998-2003: Assistant Professor, Mechanical Engineering Dept., University of Alaska Fairbanks
1997-1998: Postdoc/Technical Staff Member, Structural Dynamics and Vibration Control Department, Sandia National Laboratories, Albuquerque, NM.

Publications Relevant to the Proposed Research

1. Butcher, Eric A. and R. Lu, "Order Reduction of Structural Dynamic Systems with Static Piecewise Linear Nonlinearities," *Nonlinear Dynamics,* published online Jan. (2007).
2. Deshmukh, V., E. A. Butcher, and S. C. Sinha, "Order Reduction of Parametrically Excited Linear and Nonlinear Structural Systems," *J. Vibration and Acoustics* 128, 458-468 (2006).
3. Sinha, S. C., S. Redkar, V. Deshmukh, and E. A. Butcher, "Order Reduction of Parametrically Excited Systems: Techniques and Applications," *Nonlinear Dynamics* 41, 237-273 (2005).
4. Sinha, S. C., S. Redkar, and E. A. Butcher, "Order Reduction of Nonlinear Systems with Time-Periodic Coefficients Using Invariant Manifolds," *J. Sound and Vibration* 284, 985-1002 (2005).
5. Butcher, E. A and D. J. Segalman, "Characterizing Damping and Restitution in Compliant Impacts via Modified K-V and Higher-Order Linear Viscoelastic Models," *J. Applied Mechanics* 67, 831-834 (2000).
6. Butcher, E. A., "Clearance Effects on Bilinear Normal Mode Frequencies," *J. Sound & Vib.* 224, 305-328 (1999).

Other Publications

1. Deshmukh, V., E. A. Butcher, and E. Bueler, "Dimensional Reduction of Nonlinear Delay Differential Equations with Periodic Coefficients using Chebyshev Spectral Collocation," *Nonlinear Dynamics,* in press.
2. Voronov, S. A, A. M. Gouskov, A. S. Kvashnin, E. A. Butcher, and S. C. Sinha, "Influence of Torsional Motion on the Axial Vibrations of a Drilling Tool," *J. Computational and Nonlinear Dynamics* 2, 58-64 (2007).

3. Deshmukh, V., H. Ma, and E. A. Butcher, "Optimal Control of Parametrically Excited Linear Delay Differential Systems via Chebyshev Polynomials," *Optimal Control Applications & Methods* 27, 123-136 (2006).
4. Gouskov, A. M., S. A. Voronov, E. A. Butcher, and S. C. Sinha, "Nonconservative Oscillations of a Tool for Deep Hole Honing," *Comm. Nonlinear Science & Numerical Simulation* 11, 685-708 (2006).
5. Sinha, S. C., S. Redkar, and E. A. Butcher, "On Macromodeling of Nonlinear Systems with Time Periodic Coefficients," *Comm. Nonlinear Science & Numerical Simulation* 11, 510-530 (2006).
6. Ma, H. and E. A. Butcher, "Stability of Elastic Columns Subjected to Periodic Retarded Follower Forces," *Journal of Sound and Vibration* 286, 849-867 (2005).
7. Ma, H., V. Deshmukh, E. A. Butcher, and V. Averina, "Delayed State Feedback and Chaos Control for Time-Periodic Systems via a Symbolic Approach," *Comm. Nonlinear Science & Numerical Simulation* 10, 479-497 (2005).
8. Butcher, Eric A. and R. Lu, "Constant-Gain Linear Feedback Control of Piecewise Linear Structural Systems via Nonlinear Normal Modes," *J. Vibration and Control* 10, 1535-1558 (2004).
9. Ma, H., E. A. Butcher, and E. Bueler, "Chebyshev Expansion of Linear and Piecewise Linear Dynamic Systems with Time Delay and Periodic Coefficients Under Control Excitations", *J. Dynamic Systems, Measurement, and Control* 125, 236-243 (2003).
10. Butcher, E.A., Ma, H., Bueler, E., Averina, V., and Szabo, Z., "Stability of Linear Time-Periodic Delay-Differential Equations via Chebyshev Polynomials," *Int. J. Num. Meth. Engr.* 59, 895-922 (2004).

Other Relevant Qualifications/Activities

Awards: Inaugural holder of Chapman Endowed Professorship, Dept. of Mechanical Engineering, New Mexico State University

Reviewer of papers submitted to: *J. Vibration & Acous.*, *Int'l J. Non-linear Mech., Math. & Computer Modelling*, *J. Dyn. Sys., Meas.,& Control*, *J. Vibration &Control*, *Mechanism & Machine Theory*, *Nonlinear Dynamics, J. Computational and Nonlinear Dynamics, J. Sound & Vibration*, various conferences

Reviewer of proposals submitted to the National Science Foundation and the Army Research Office

Symposium organizer for ASME IDETC 2001, 2003, 2005, 2007; ICSV 2002, 2003

PI on two major grants: from AFOSR (*Order Reduction of Large Scale Systems via Nonlinear Normal Modes*, $475,911, May 15, 2001-Nov. 14, 2004) and NSF (*Symbolic Stability and Bifurcation Analysis of Time-Periodic Differential-Delay Equations: Applications to High-Speed Machining Models*, $254,648, Sept. 6, 2001-Jan. 31, 2006)

BIOGRAPHICAL SKETCH - IGOR SEVOSTIANOV

Associate Professor, Department of Mechanical and Aerospace Engineering
P.O. Box 30001 Las Cruces, NM 88003-8001
Tel: (505) 646-3322 *Email:* igor@me.nmsu.edu

Professional Preparation.
St. Petersburg (Leningrad) University, Russia (USSR) Mechanics B.S./ M.S., 1988
St. Petersburg (Leningrad) University, Russia (USSR) Solid Mechanics PhD, 1993

Appointments.

- 2001 – present Assistant and Associate Professor

Dept Mech. Eng., New Mexico State University, Las Cruces, NM

- 1998-2001 Senior Research Associate

Dept Mech. Eng., Tufts University, Medford, MA

- 1997-1998 Senior Research Associate

Dept Mech. Eng., University of Natal, Durban, South Africa

- 1993-1996 Visiting Scientist

Max-Planck Research Unit "Mechanics of Heterogeneous Solids", Dresden, Germany

Grants.

Current grant

- "Novel Nanoparticle-Filled Matrices for Thermal Stress Reduction in Polymer Matrix Composites: Multi-Scale Modeling and Experimental Validation" from NASA. (2007-2009)

Pending proposals

- Pending proposal: Assessment of mechanical performance of metal foams and dense metals with deteriorating microstructure by means of electric conductivities (AFOSR)

Former research grants

- "Acquisition of a Tensile and Compression Test Capability for Characterization of Advanced Materials" from NSF (2005-2007)
- "Macroscopic stress-strain relations with microcracks – generated inelasticity" from Sandia National Labs (2004).
- "Critical Issues and Unresolved Problems in Computational Modeling Supporting Ceramic Armor Analysis" from Sandia National Labs (2003)

Awards

NMSU Research Council Award for Exceptional Achievements in Creative Scholarly Activity, 2006.

ME Academy Professor of the Year, 2007.

Ten key publications. (Total number of publication - 84, current ISI citation index 163, self references and references by co-authors are excluded).

Sevostianov, I. and Kachanov, M. Nanoparticle reinforced materials: effect of interphase layers on the overall properties. *International Journal of Solids and Structures* 44 (2007) 1304-1315.

Sevostianov, I., Kováčik, J. and Simančík, F. Elastic and electric properties of closed-cell aluminum foams. Cross-property connection *Materials Science and Engineering, A*-420, 87-99.

Sevostianov, I. and Kachanov, M. Plastic yield surfaces of anisotropic porous materials in terms of electric conductivities. *Mechanics of Materials*, **38**, 2006, 908-923.

Kachanov, M. and Sevostianov, I. On quantitative characterization of microstructures and effective properties. *International Journal of Solids and Structures* **42**, 2005, 309-336

Sevostianov, I., Kachanov, M., Ruud, J., Lorraine, P., Dubois, M. Quantitative characterization of microstructures of plasma-sprayed coatings and their conductive and elastic properties. *Materials Science and Engineering-A,* 386, 2004, 164-174.

Sevostianov, I. and Kachanov, M. Connection between elastic and conductive properties of microstructures with Hertzian contacts. *Proceedings of the Royal Society of London: Mathematical, Physical & Engineering Sciences* A-460, 2004, 1529-1534.

Sevostianov, I. Explicit relations between elastic and conductive properties of a material containing annular cracks. *Philosophical Transactions of the Royal Society of London: Mathematical, Physical and Engineering Sciences*, 361, 2003, 987-999.

Sevostianov, I. and Kachanov, M. Explicit cross-property correlations for anisotropic two-phase composite materials. *Journal of the Mechanics and Physics of Solids*, 50, 2002, 253-282.

Sevostianov, I., Gorbatikh, L. and Kachanov, M. Recovery of information on the microstructure of porous/microcracked materials from the effective elastic/conductive properties. *Materials Science and Engineering A*, 318, 2001, 1-14.

Kachanov, M., Sevostianov, I. and Shafiro, B. Explicit cross-property correlations for porous materials with anisotropic microstructures, *Journal of the Mechanics and Physics of Solids*, 49, 2001, 1-25.

Collaborators during last ten years (in alphabetical order of the cities)

University of New Mexico, Albuquerque, NM, USA (L.Gorbatikh);
Institute of Materials and Machine Mechanics, Slovak Academy of Sciences, Bratislava, Slovakia (J. Kovacik, F. Simancik)
TU Dresden, Germany (W.Pompe, A.Gorbunoff, S.Lampenscherf);
University of Natal, Durban, South Africa (S.Adali, C. von Klemperer, V.Verijenko).
Durban Institute of Technology, South Africa (P.Tabakov)
TuftsUniversity, Medford, MA (M.Kachanov, B.Shafiro, E.Karapetian)
UNAM, Mexico City, Mexico (F.Sabina)
Petrozavodsk University, Russia (V.Levin)
General Electric R&D Schenectady, NY (J.Ruud)
Max-Planck Institute for Metals Research, Stuttgart, Germany (T.Michelitsch, H.Gao)
St Petersburg Sate University, Russia (N.Morozov)
Swiss Federal Laboratories for Materials Testing and Research (EMPA), Thun, Switzerland (N.Margadant, S.Sigman)
ALSTOM Power AG, Zurich, Switzerland (A.Zagorsky)

BIOGRAPHICAL SKETCH – ANDREI ZAGRAI

Department of Mechanical Engineering,
New Mexico Institute of Mining and Technology, Socorro, NM, USA
Phone: 505-835-5636, Fax: 505-835-5209, e-mail*:* *azagrai@nmt.edu*.

EDUCATION

Ph. D. Mechanical Engineering, University of South Carolina, 2002.
M. E. Department of Acoustics, Taganrog State University of Radio-Engineering, Russia, 1997.
B. E. Department of Acoustics, Taganrog State University of Radio-Engineering, Russia, 1996.

PROFESSIONAL EXPERIENCE

8/06–present Assistant Professor, Department of Mechanical Engineering, New Mexico Institute of Mining and Technology, Socorro, NM
7/02 – 7/06 Post-Doctoral Fellow and Research Scientist, Department of Civil, Ocean and Environmental Engineering, Davidson Laboratory, Stevens Institute of Technology, Hoboken, NJ
8/98 – 5/02 Research and Teaching Assistant, Department of Mechanical Engineering, University of South Carolina, Columbia, SC

SELECTED HONORS, AWARDS, AND SCHOLARSHIPS

- March, 2007 – Air Force Summer Faculty Fellow (SFFP) for the 2007.
- March, 2002 – 1st Place best student paper award of *SPIE's 7th Symposium on NDE for Health Monitoring and Diagnostics*.
- December 21st, 2001 – 2nd Prize best student paper award in structural acoustics and vibration. Acoustical Society of America, American Institute of Physics
- April 20th, 1998 - The National Scholarship of the President of Russian Federation for Education Abroad
- September 10th, 1996 – The National Scholarship of the President of Russian Federation.

SYNERGISTIC ACTIVITIES

Reviewer for Professional Journals: Structural Health Monitoring, Journal of the Acoustical Society of America (JASA), Journal of Intelligent Material Systems and Structures, ASME Journal of Vibration and Acoustics, ASME Journal of Pressure Vessel Technology, Smart Materials and Structures, Mechatronics, Structural Engineering and Mechanics, Measurement Science and Technology, IEEE Transactions on Ultrasonics, Ferroelectrics, and Freq. Control.
Reviewed proposals for: NSF, AFOSR, Natural Sciences and Engineering Research Council of Canada (NSERC), and books proposals for Cambridge University Press.
Invited and Keynote Conference Presentations:

- December, 2005 – keynote speaker, *International Conference on Advances in Structural Dynamics and its Applications* (*ICASDA*), 7-9 Dec. 2005, Visakhapatnam, India.
- May, 2006 invited session address, *106-SDM-67 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Newport, RI.
- June, 2007 keynote paper, *Second World Congress on Engineering Asset management and the Fourth International Conference on Condition Monitoring (WCEAM)*, June 11-14, Harrogate, United Kingdom

RELEVANT PUBLICATIONS

1. Zagrai, A., Donskoy, D., Chudnovsky, A., Golovin, E., (2006) "Nonlinear Acoustic Structural Health Monitoring," ***Invited Paper***, 106-SDM-67 *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Newport, RI.
2. Giurgiutiu, V., Zagrai, A. (2005) "Damage Detection in Thin Plates and Aerospace Structures with the Electro-Mechanical Impedance Method", International Journal of Structural Health Monitoring, Vol. 4, N. 2, pp. 99-118.
3. Zagrai, A., (2005) "Intelligent Active Sensors for Structural Health Monitoring," ***Keynote Paper***, *Proceedings of the International Conference on Advances in Structural Dynamics and its Applications* (ICASDA), pp. 568-598, 7-9 Dec. 2005, Visakhapatnam, India.
4. Giurgiutiu, V., Zagrai, A.N. (2002) "Embedded Self-Sensing Piezoelectric Active Sensors for On-line Structural Identification," Transactions of ASME, *Journal of Vibration and Acoustics*, Vol. 124. N. 1, pp. 116-125.
5. Zagrai, A.N., Giurgiutiu, V. (2001) "Electro-Mechanical Impedance Method for Crack Detection in Thin Plates", *Journal of Intelligent Material Systems and Structures*, Vol. 12, N. 10, - October 2001, pp. 709-718.

Other publications

1. Zagrai, A.N. and Donskoy, D.M. (2005) "A "Soft Table" for the Natural Frequencies and Modal Parameters of Uniform Circular Plates with Elastic Edge Support", *Journal of Sound and Vibration*. Vol. 287, N. 1-2, pp. 343-351.
2. Zagrai, A., Donskoy, D. and Ekimov, A. (2005) "Structural Vibrations of Buried Land Mines", *Journal of the Acoustical Society of America* (JASA), Vol. 118, N. 6, pp. 3619-3628.
3. Giurgiutiu, V., Zagrai, A.N., Bao, J.J., (2004) "Damage Identification in Aging Aircraft Structures with Piezoelectric Wafer Active Sensors", *Journal of Intelligent Material Systems and Structures*, Vol. 15, N. 9/10, September/October 2003, pp. 673-687.
4. Giurgiutiu, V., Zagrai, A.N., Bao, J.J., Redmond, J.M., Roach, D., Rackow, K. (2003) "Active Sensors for Health Monitoring of Aging Aerospace Structures", *International Journal of Condition Monitoring and Diagnostic Engineering Management* (COMADEM), UK, Vol. 6, N. 1, pp. 3-21.
5. Giurgiutiu, V., Zagrai, A.N., Bao, J.J. (2002) "Piezoelectric Wafer Embedded Active Sensors for Aging Aircraft Structural Health Monitoring", *International Journal of Structural Health Monitoring*, Vol. 1, N. 1, pp. 41-61.

CURRENT AND PENDING SUPPORT (by investigator, in alphabetical order)

Sayavur Bakhtiyarov

Current Support
Name of Project: "Technology on In-Situ Gas Generation to Recover Residual Oil Reserves"
Position on Project: Principal Investigator
Start of Project: October 1, 2005
End of project: September 30, 2007
Funding Agency: U.S. Department of Energy, National Energy Technology Laboratory, Grant No. DE-FC26-05NT15478
Total Funding Support for Entire Performance Period: $700,985
Percentage of effort – 25 %

Pending Support
1. Name of Project: **"**Algae Produced Biodiesel**"**
Position on Project: Co-Principal Investigator
Start of Project: October 1, 2007
End of project: September 30, 2008
Funding Agency: New Mexico State Energy Innovation Fund
Total Funding Support for Entire Performance Period: $730,028
Percentage of effort – 16.7 %

2. Name of Project: "A Novel Approach to Prevent Volatile Organic Compound Emissions in Storage Tanks"
Position on Project: Co-Principal Investigator
Start of Project: October 1, 2007
End of project: February 29, 2009
Funding Agency: ANSF/CRDF Azerbaijan-U.S. Bilateral Grants Program
Total Funding Support for Entire Performance Period: $40,000
Percentage of effort – 8.3 %

Thomas Burton

Current Support
Name of Project: Army High Performance Computing Research Center
Position on Project: NMSU Technical Lead
Start of Project: June 1, 2007
End of project: May 31, 2012
Funding Agency: US Army Research Office
Grant No. not yet specified
Total Funding Support for Entire Performance Period: $3,750,000 (total NMSU share)
Percentage of effort – 10%

Pending Support- none

<u>Eric A. Butcher</u>

Current and Pending Support

Dr. Butcher currently has no current or pending support.

<u>Igor Sevostianov</u>

Current Support
Name of Project: “Novel nanoparticle-filled matrices for thermal stress reduction in polymer matrix composites: multi-scale modeling and experimental validation”
Position on Project: co-PI (subcontract from Texas Tech University)
Start of Project: January, 2007
End of project: December, 2009
Funding Agency: NASA
Total Funding Support for Entire Performance Period: $85,000 (I. Sevostianov share)
Percentage of effort- 12.5%

Name of Project: “Assessment of mechanical performance of metal foams and dense metals with deteriorating microstructure by means of electric conductivities”
Position on Project: Principal Investigator
Start of Project:
End of project:
Funding Agency: U.S. Department of Defense, Air Force Office of Scientific Research (AFOSR)
Total Funding Support for Entire Performance Period: $299,991
Percentage of effort – 12.5%

<u>Andrei Zagrai</u>

Current Support
Name of Project: “Exploring the Acoustic Nonlinearity for Monitoring Complex Aerospace Structures”
Position on Project: Principal Investigator
Start of Project: June 1, 2007
End of project: November 31, 2007
Funding Agency: U.S. Department of Defense, Air Force Office of Scientific Research (AFOSR)
Total Funding Support for Entire Performance Period: $45,295
Percentage of effort – 10 %

Pending Support

1. Name of Project: **"**Nonlinear Structural Health Monitoring of the Responsive Space Satellite Systems using Magneto Elastic Active Sensors (MEAS)**"**
Position on Project: Principal Investigator
Start of Project: October 1, 2007
End of project: September 30, 2010
Funding Agency: U.S. Department of Defense, Air Force Office of Scientific Research (AFOSR)
Total Funding Support for Entire Performance Period: $259,897
Percentage of effort – 10 % each year

2. Name of Project: "Undergraduate Energetic Materials and Explosives Laboratory."
Position on Project: Co-Principal Investigator
Start of Project: October 1, 2007
End of project: September 31, 2008
Funding Agency: NSF CCLI
Total Funding Support for Entire Performance Period: $150,000
Percentage of effort – 8.3 %