REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-01-
0469

Public reporting burden for this collection of information is estimated to average 1 hour per response, gathering and maintaining the data needed, and completing and reviewing the collection of informatior collection of information, including suggestions for reducing this burden, to Washington Headquarters Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, a sources, ect of this Jefferson 3.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 2001

3. R
FIN CHNICAL REPORT 1 Apr 00 - 31 Mar 01

4. TITLE AND SUBTITLE
(DURIP 00) EXPERIMENTAL INTELLIGENT STRUCTURS

5. FUNDING NUMBERS
F49620-00-1-0232

3484/US
61103D

6. AUTHOR(S)
MARK J. SCHULZ, MANNUR J. SUNDERESAN, AND ANINDYA GHOSHAL

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NORTH CAROLINA A&T STATE UNIVERSITY
DEP OF MECHANICAL ENGINEERING
GREENSBORO, NC 27411

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
801 N. RANDOLPH STREET, ROOM 732
ARLINGTON, VA 22203-1977

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE, DISTRIBUTION IS UNLIMITED

20011005 138

13. ABSTRACT *(Maximum 200 words)*

This instrumentation grant requested equipment to establish an Intelligent Structures Laboratory for the R&D of cybernetic or artificially intelligent structures. The equipment requested included a mechanical testing machine, signal processing instrumentation, piezoceramic materials, software for a laser vibrometer, oscilloscopes, and other instrumentation. Experimentation was performed using some of the equipment purchased in this grant. Salary support for the research was from other research grants. The equipment purchased will be the basis for long-term experimental research in the area of intelligent structures. The equipment and instrumentation requested was ordered and received and all is operating except for the mechanical testing machine which is being installed. Analytical studies and simulations of intelligent structures and no-load testing of an artificial neural system are being performed and some interesting results from these activities are highlighted in this report. The next step in the work is to test an artificial neural system under loading using the mechanical testing system. The intelligent structure to be tested is a composite component with the neural system attached. The structure will be tested under realistic load conditions to verify that the neural system can detect initiating damage in the panel. Further studies will be to develop the algorithms and the sensor system architecture needed to provide strain and acoustic emission information that can be used to optimize the performance while minimizing the fatigue of the structure. Development of a self-regulating or intelligent structure that can sense and optimize its performance while minimizing fatigue damage is the goal of this research.

14. SUBJECT TERMS

15. NUMBER OF PAGES
12

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
U	U	U	

JUL 16

Final Report for the DURIP Grant

EXPERIMENTAL INTELLIGENT STRUCTURES

Sponsored by the DOD-AIR FORCE/AFOSR

Agreement No. F49620-00-1-0232

Award Period 04/01/00 to 03/31/01

By

Mark J. Schulz, Mannur J. Sundaresan, Anindya Ghoshal
Intelligent Structures and Mechanisms (ISM) Laboratory
Department of Mechanical Engineering
North Carolina A&T State University
Greensboro, NC 27411

Technical Monitors

Brian P. Sanders, MAJOR, USAF
(Initial Technical Monitor)
NA 703-696-7259

Daniel J. Segalman
(Final Technical Monitor)
Air Force Office of Scientific Research
801 N. Randolph St.
Arlington, VA 22203
Ph. 703-696-8451
Fax; 703 696-8451
Email: daniel.segalman@afosr.af.mil

July 10, 2001

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

This instrumentation grant requested equipment to establish an Intelligent Structures Laboratory for the research and development of cybernetic or artificially intelligent structures. The equipment requested included a mechanical testing machine, signal processing instrumentation, piezoceramic materials, software for a laser vibrometer, oscilloscopes, and other instrumentation. This summary gives an overview of the accomplishments made during the one-year period of performance of the grant. Experimentation was performed using some of the equipment purchased in this grant. Salary support for the research was from other research grants. The equipment purchased will be the basis for long-term experimental research in the area of intelligent structures.

The equipment and instrumentation requested was ordered and received and all is operating except for the mechanical testing machine which is being installed. Analytical studies and simulations of intelligent structures and no-load testing of an artificial neural system are being performed and some interesting results from these activities are highlighted in this report. The next step in the work is to test an artificial neural system under loading using the mechanical testing system. The intelligent structure to be tested is a composite component with the neural system attached. The structure will be tested under realistic load conditions to verify that the neural system can detect initiating damage in the panel. Further studies will be to develop the algorithms and the sensor system architecture needed to provide strain and acoustic emission information that can be used to optimize the performance while minimizing the fatigue of the structure. Development of a self-regulating or intelligent structure that can sense and optimize its performance while minimizing fatigue damage is the goal of this research. One MS student, one Ph.D. student, two research adjunct faculty, and one faculty member have used the equipment thus far.

1. RESEARCH PERFORMED

The initial application investigated for the intelligent structure is Structural Condition Monitoring (SCM). Present techniques for in-situ real-time SCM may not be sensitive enough or cost-effective enough for application to large structures and structures that have complex geometry such as joints, ribs, varying thickness, fasteners, and varying curvature. Present techniques are also difficult to use with structures that contain hybrid materials or materials that are highly damped such as honeycomb sandwich structures. The most promising of the present techniques use Lamb wave propagation in the plane of the material to detect damage. These methods can detect damage accurately in simple structures by measuring wave reflections from defects [1], or by transmitting and receiving waves and casting shadows [2]. However, for many applications these approaches may be too complex because large arrays of sensor/actuator elements will be required. The associated wiring, instrumentation, amplification, multiplexing, and computational resources required to implement these methods on a large scale may be prohibitive in terms of cost, added weight, and reliability. Another difficulty with these methods is that individual monolithic piezoceramic wafers are used as the sensor/actuator elements. These elements and their connections form stress concentrations in composite materials that could lead to cracking and failure of the structure.

To overcome these limitations, we are designing long active fiber materials [3-4] specifically for use as nerves for SCM. The nerves will be built using piezoceramic ribbons and new connectivity methods and electrode patterns that we have developed to improve the sensitivity and practicality of using active fiber materials for structural sensing. The construction of the nerves is based on the biological nerve cell [5], and a concept is shown in Figure 1. The nerve is constructed starting with PZT Active Fiber Composite (AFC) ribbon fibers [6] shown in Figure 2 to form structural nerves as shown in Figure 3.

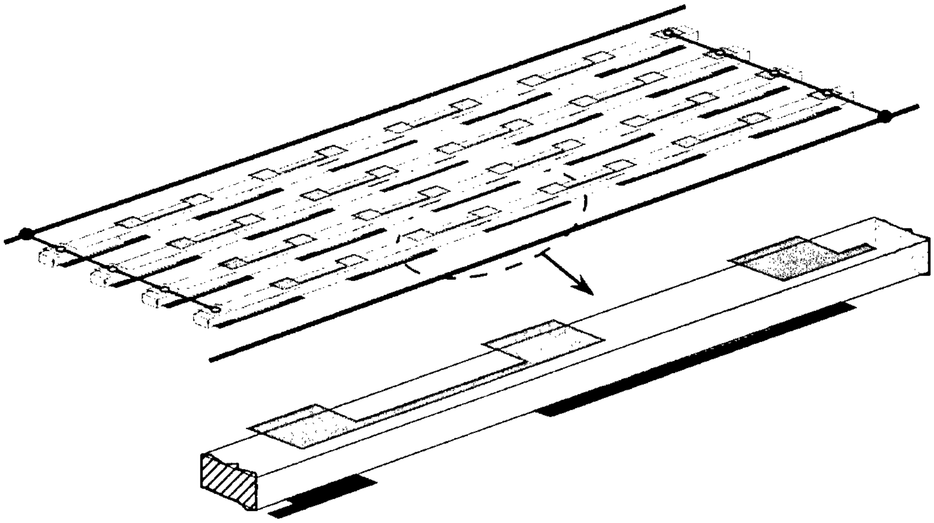

Figure 1. The artficial nerve concept with piezoceramic ribbon fibers.

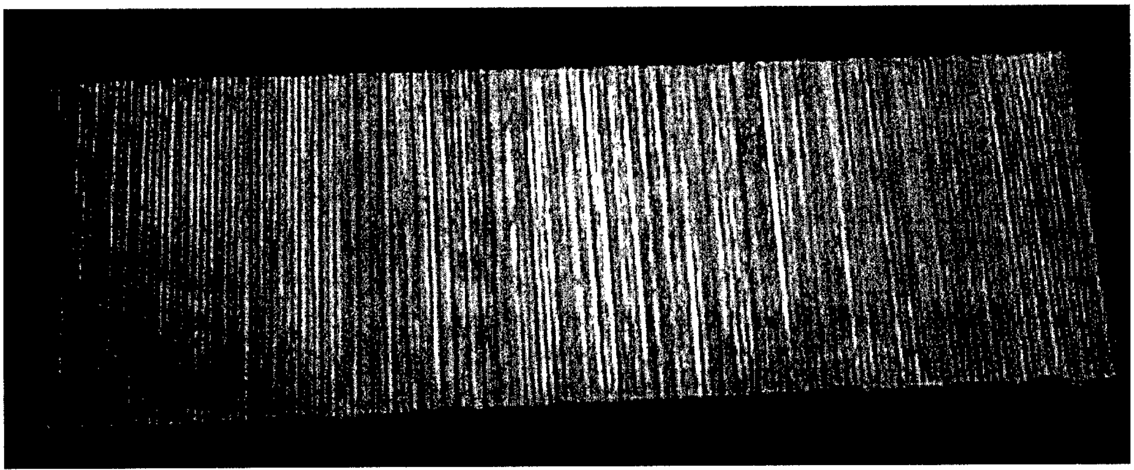

Figure 2. Preform to be used in construction of AFC with five PZT ribbons AR=3:1, width=450 microns, thickness=150 microns. (Photo from NCA&T/CeraNova Corporation).

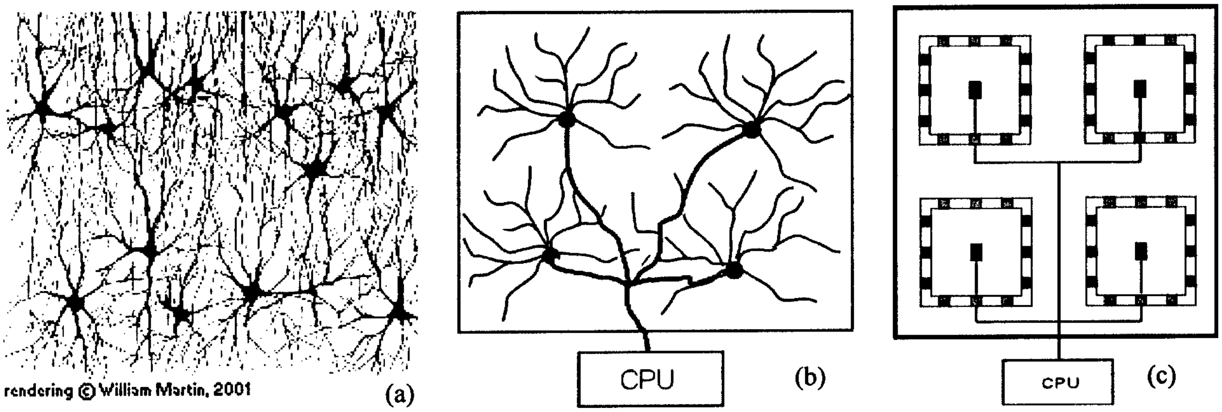

Figure 3. Neurons; (a) biological, (b) structural with branch dendrites, (c) structural with square receptor dendrites.

We have developed a simulation code to study the benefits of the nerve sensor. The algorithm computes the response of the nerve caused by acoustic waves propagating in a plate. The algorithm uses the physical parameters of the nerve, the one-dimensional piezoelectric constitutive equation, and a specified acoustic waveform, and it computes the voltage as the wave passes over the sensor nodes of the nerve. The electrical circuit model of the sensor nerve is shown in Figure 4.

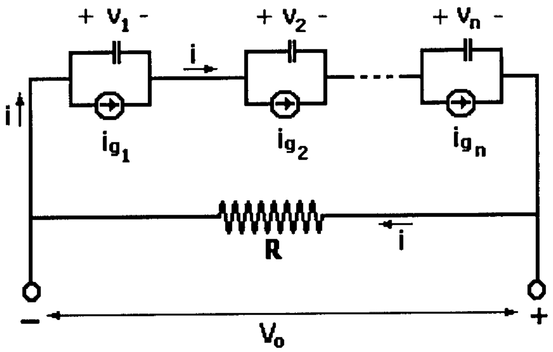

Figure 4. Circuit model of the nerve sensor with nodes 1,2,...n connected in series.

The neural system is being investigated analytically [7-13] considering passive sensing of Acoustic Emissions (AE) at high frequency to detect damage. The modeling performed to study the continuous sensor couples the elastic equations of a plate structure to the piezoelectric constitutive equations. An elastic model of a plate is used to simulate the response of the sensor to an impulse generated by a PZT patch at the center bottom of the panel. The average strains over the area of the sensor are used to compute the voltage output from the sensor. The voltage output is computed based on the piezoelectric constitutive equations and the thickness and the capacitance of the sensor. The simulation is performed for a composite fiberglass plate with an integrated neural sensor. Figure 5 shows the pattern of wave propagation in the plate as a result of an impulse input to a piezoceramic patch at the center of the panel. The plate displacement due to wave propagation is shown at different times. Different designs of actuators and sensor can be studied using this model.

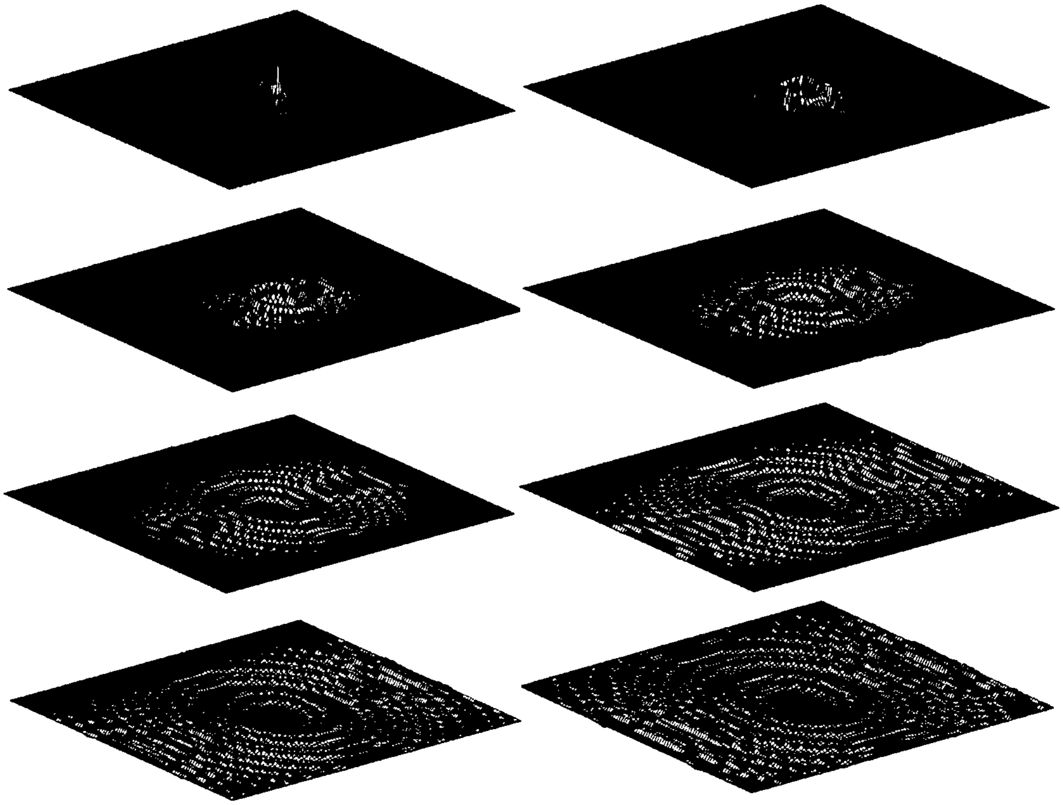

Figure 1. Simulation of wave propagation from the center of a panel at 10, 60, 110, 160, 210, 260, 310, 360 micro-sec due to center patch actuation. The actuator dimensions are 1"x2". There are 100 modes in the solution and the time step is 1 microsecond.

Damage in a plate was simulated using the fiberglass plate shown in Figure 6. A lead break from a 0.3mm mechanical pencil was put near the center of the plate. The simulation and experimental response are shown in Figure 7. The simulation results shown were scaled (decreased in amplitude by a factor of 7.5) to match the amplitude of the experimental results. It is suspected that there is some additional resistance or capacitance in the experimental circuit that is not included in the simulation that causes the simulation to predict a greater voltage amplitude. Also, the boundary condition in the experiment is stiffer than the simply supported boundary in the simulation. This may make the test response have a smaller amplitude. The circuit modeling and boundary condition are being further investigated. Nine sensor nodes are used to form the neural sensor, yet there is only one output signal from the sensor. The acoustic emission response was detected and the experiment and scaled simulation compared favorably, especially considering the difficulty in modeling acoustic waves in panels. This one channel sensor can detect AE that occur at any location in the panel.

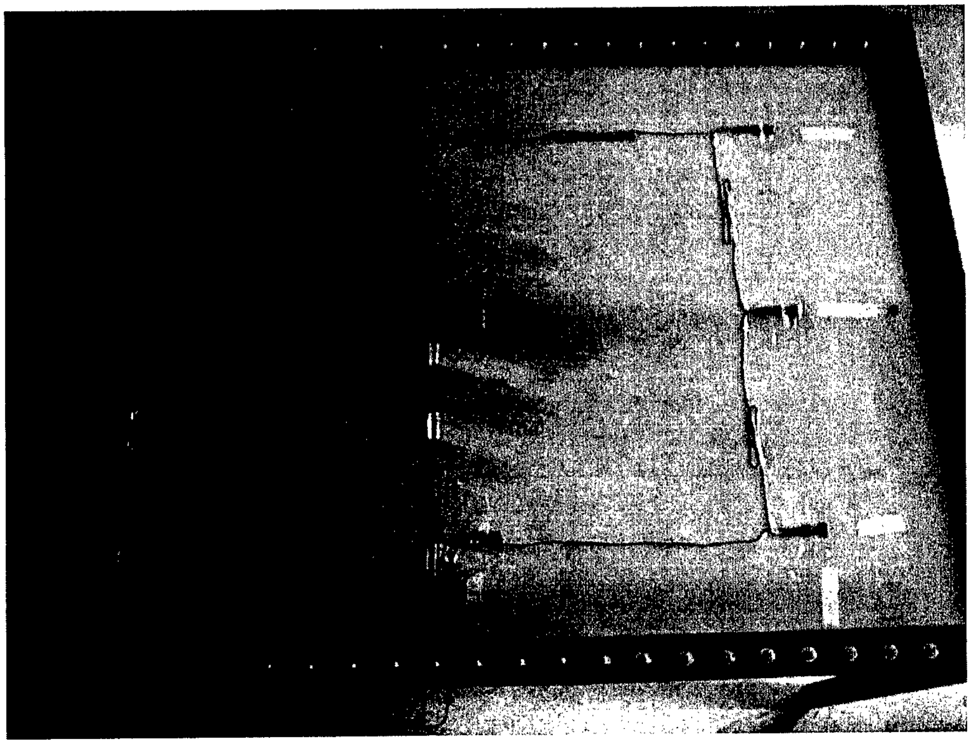

Figure 6. A fiberglass panel with a continuous sensor with nine PZT nodes.

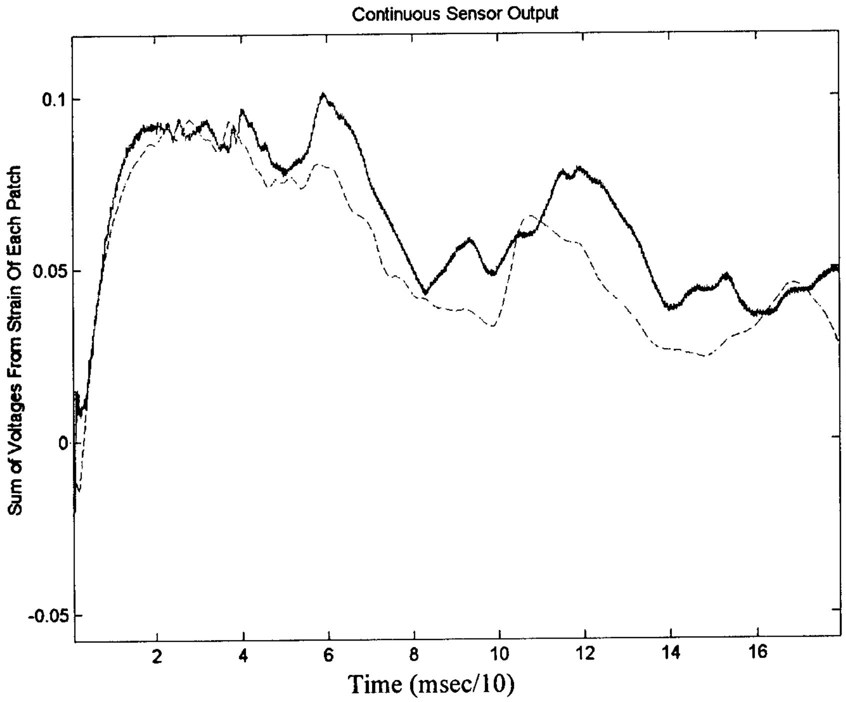

Figure 7. Voltage response of the continuous nerve due to a 0.3 mm lead break. Scaled simulation result (dashed) shown with experiment result (solid).

2. EDUCATIONAL ACTIVITIES AND PUBLICATIONS

Also important in this project are to: (i) Develop intellectual capital (new scientists), (ii) Strengthen the nations physical infrastructure in science and engineering, (iii) Integrate research and education, and (iv) Promote partnerships and alliances. Educational activities in this project center on transitioning the research accomplishments to the academic and industrial community. Dr. Schulz will be teaching a new course entitled "Introduction to Smart Structures" this fall semester and he will use some of the modeling done for the research in the course. This project also promotes a cross-disciplinary infrastructure that transcends departmental, institutional, industrial and governmental barriers and lends itself to the integration of research and education in the vital field of smart and advanced materials. A small business, CeraNova Corporation, is supplying the active fiber composite preforms used to build the nerve sensors. One MS student, one Ph.D. student, two research associates, and one faculty member have used the equipment thus far.

Publications that were partially sponsored by this grant are listed below.

1. Ghoshal, A., Martin, W. N., Sundaresan, M. J., Schulz M. J., and Ferguson, F., *"Active Wave Propagation and Sensing in Plates,"* Third Workshop on Structural Health Monitoring, Stanford, CA, September 12-14, 2001, abstract submitted.
2. Martin Jr., W.N., Ghoshal, A., Lebby, G., Sundaresan, M.J., Schulz, M.J., Pratap, P.R., *"Artificial Nerves for Structural Health Monitoring,"* Third Workshop on Structural Health Monitoring, Stanford, CA, September 12-14, 2001.
3. Schulz, M.J., Chattopadhyay, S., Sundaresan, M.J., Ghoshal, A., Martin, W.N., Pratap, P.R., *"Piezoelectric Materials for an Artificial Neural System,"* ASME WAM, November 16, 2001, New York, NY.

3. LIST OF EQUIPMENT PURCHASED

The list of equipment and instrumentation purchased is shown in Table 1.

Table 1. List of equipment purchased.

ITEM	COST
1. Material Test System, 22,000Lb Tension (MTS Inc. Model 810.22)	87000
2. Computer security device	49
3. Notebook computer for signal processing	4280
4. Laser software update 6.0 and zoom option for FFT (Polytec PI)	11097
5. PC 450MHz, 384MB RAM, to host LABVIEW board (Gateway 2000)	9,102
6. MATLAB License	763
7. Digital Oscilloscope, 4 channel, 200MHz (LeCroy), quantity two	18,112
8. PZT, IDT, quantity 6	770
9. High voltage Amplifier to pole/drive AFC (Trek)	13,540
11. AFC skins (5) to build an intelligent structure (CeraNova Corp.)	1,000
12. Electrical supplies, fixturing, Neural Net. Software, cables, print cart.,etc.	5,000
TOTAL Expenditures	150713

4. FUTURE WORK

The mechanical test machine is being installed and then the main experimental work will begin. The objectives of the experimentation are:

1. Verify the performance of the neural sensor to detect damage under realistic load conditions.
2. Determine the fundamental mechanisms and microstructural features of evolving fatigue damage in fiber composite materials and use this understanding to design the most effective sensor system to detect/and or repair the damage.
3. Develop and test a repair method to localize the damage (prevent propagation).
4. Perform strength testing of a composite with the integrated neural sensor to determine if the sensor can survive the cyclic loading.
5. Develop a self-regulating, condition-based fault-tolerant control method technique that can manage the external loading to reduce the likelihood of the occurrence and propagation of damage.

5. REFERENCES

1. Wang, C., Chang, F., *"Diagnosis of Impact Damage in Composite Structures with Built-In Piezoelectrics Network,"* Proceedings of the SPIE, Vol. 3990, p. 13, 2000.
2. Schwartz, W.G., Read, M.E., Kremer, M.J., Hinders, M.K., Smith, B.T., *"Lamb Wave Tomographic Imaging System for Aircraft Structural Health Assessment,"* SPIE Conference on NDE of Aging Aircraft, Airports, and Aerospace Hardware III, Vol. 3586, P. 292, 1999, Newport Beach, CA.
3. Bent, A. A., Hagood, N. W., *"Piezoelectric Fiber Composites with Interdigitated Electrodes," Journal of Intelligent Material Systems and Structures*, 8, 1998.
4. Continuum Control Corporation, 45 Manning Park, Billerica, MA 01821.
5. Zigmond, M.J., Boom, F., Landis, S.C., Roberts, J.L., Squire, L.R., Fundamental Neuroscience, Acacemic Press.
6. CeraNova Corporation, 101 Constitution Boulevard, Suite D, Franklin, MA 02038-2587.
7. Sundaresan, M.J., Ghoshal, A., and Schulz, M.J., "*Sensor Array System*," patent application, 6/00.
8. Ghoshal, A., Martin, W. N., Sundaresan, M. J., Schulz M. J., and Ferguson, F., *"Wave Propagation Sensing for Damage Detection in Plates,"* Third Workshop on Structural Health Monitoring, Stanford, CA, September 12-14, 2001, abstract submitted.
9. Sundaresan, M.J., Schulz, M.J., Ghoshal, A., Pratap, P., *"A Neural System for Structural Health Monitoring,"* SPIE 8th international Symposium on Smart Materials and Structures, March 4-8, 2001.
10. Martin Jr., W.N., Ghoshal, A., Lebby, G., Sundaresan, M.J., Schulz, M.J., Pratap, P.R., *"An Artificial Neural System for Structural Health Monitoring,"* Third Workshop on Structural Health Monitoring, Stanford, CA, September 12-14, 2001, abstract submitted.
11. Schulz, M. J. Sundaresan, M.J., Ghoshal, A., Martin, W.N., *"Evaluation of Distributed Sensors for Structural Health Monitoring,"* abstract submitted, ASME Conference, Pittsburgh, PA, 2001.
12. Sundaresan, M. J. Schulz, M.J., Ghoshal, A., Ferguson, F., "*Active Fiber Composite Sensors and Actuators*," ACUN-3 International Composites Meeting, Technology Convergence in Composites Applications, Univ. of New South Wales, Sydney, Australia, February 6-9, 2001.
13. Ghoshal, A., Sundaresan, M.J., Schulz, M.J., Pai, P.F., *"Continuous Sensors for Structural Health Monitoring,"* Adaptive Structures and Material Systems Symposium at the International Mechanical Engineering Congress and Exposition Winter Annual Meeting of the ASME, Nov. 5-10, 2000, Walt Disney World Dolphin, Orlando, Fla.

6. ACKNOWLEDGMENT

The students and faculty members are grateful for the opportunity to have the equipment to perform our research. We believe that the neural system and the technology being developed for self-regulating structures will improve future air vehicles and other Air Force systems.