AFRL-AFOSR-VA-TR-2015-0230

High Performance Artificial Muscles Using Nanofiber and Hybrid Yarns

Ray Baughman
UNIVERSITY OF TEXAS AT DALLAS

07/14/2015
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTD
Arlington, Virginia 22203
Air Force Materiel Command

High Performance Artificial Muscles Using Twist-Spun Nanofiber and Hybrid Yarns

PI and co-PI: Ray H. Baughman and Michael Kozlov, University of Texas at Dallas

Grant FA9550-12-1-0211 (4/15/2012 – 4/14/2015)

Motivation:

❖ Improved tensile and torsional actuators are needed for both micro and macro DoD applications.

Objective:

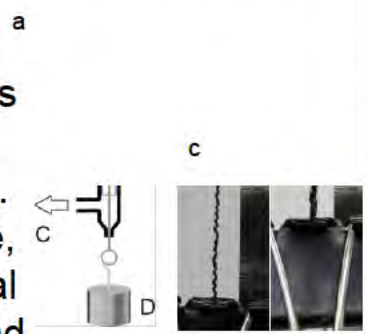
❖ Develop new tensile and torsional artificial muscles that provide giant stroke, fast response, high force generation, and long cycle life. Optimize energy conversion efficiencies.

Approaches:

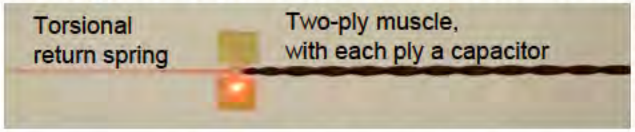
❖ Thermally powered twisted guest@CNT yarn
❖ Sorptive-powered twisted guest@CNT yarn
❖ Coiled polymer muscles from fishing line
❖ Twisted dielectric polymer muscle fibers
❖ Coiled solid-state electrochemical muscles

Recent Discoveries:

❖ Extended thermal hybrid yarn muscles to fast muscles powered by liquid sorption/ desorption by silicone guest. Muscles provide 50% stroke, 31X the work/cycle of natural muscles, 1 Hz cycle rate, and an energy conversion efficiency of up to 16%. Demonstrated the use of these silicone@CNT yarn muscles as a control valve for liquid flow.



❖ Demonstrated electrically powered dielectric polymer fiber muscles that generated 4.5% tensile stoke, 800 rpm torsional rotation speed, and 100X higher torsional stroke than any prior-art muscle that is non-thermal and non-electrochemical. Muscles are based on our project-developed super-elastic CNT sheath/rubber core conducting fibers that enable 2470% stretch and giant twist insertion without conductance loss.



Torsional mechanism is new: tensile actuation drives torsional actuation

❖ Demonstrated all-solid-state electrically powered coiled CNT fiber muscles that generate 24% tensile stroke and provide 3.2% energy conversion efficiency (twice that of our CNT fiber muscles and 10X that of conducting polymer muscles). They maintain stroke without consuming significant energy.

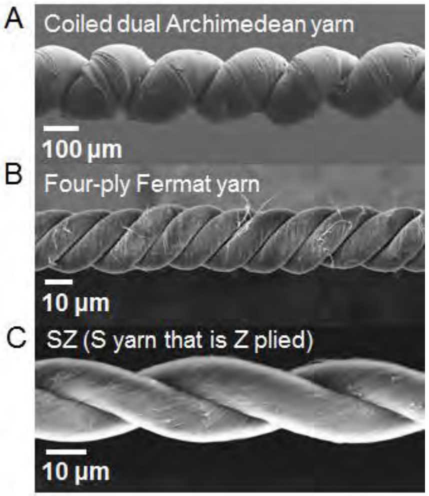
Impacts:

Publication of polymer muscles (*Science*, 2014) generated TV, radio, and other world-wide news. In 2014, Lintec, Inc. started a laboratory close to UTD to commercialize CNT technology that we licensed and muscles technology for which we provided an option to license (world-wide patent nationalization resulted).

Results Overview for the AFOSR Project (4/15/2012 -4/14/2015) on

"High Performance Artificial Muscles Using Twist-Spun Nanofiber and Hybrid Yarns"

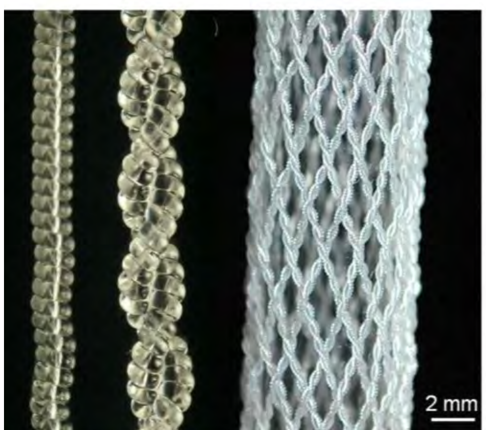
1. Work on twist-spun hybrid yarn muscles fast realized, patent-filed, and published in *Science* before 2012 ended. Recent results are in *Nature Comm.* (2014) & etc.



Mechanism: The volume change of guest in twisted or coiled CNT fiber drives thermal torsional and tensile actuation.

Realized Performance: (1) Average power density during muscle contraction of 28 kW/kg (85 times that for skeletal muscle). (2) Tensile contraction exceeding 50%. (3) Millions of reversible tensile actuation cycles at 1200 cycles/minute. (4) Torsional stroke (250°/mm) of 1000 times prior art. (5) Millions of torsional actuation cycles obtained, where a muscle spins a rotor at 11,500 rpm.

2. Above advance led to "Artificial Muscles From Fishing Line and Sewing Thread", which was patent filed and then published in *Science* in 2014.



Mechanism: Thermally powered axial and radial dimension changes of twisted polymer fiber drives giant torsional actuation, as well as giant tensile stroke when the polymer fiber is coiled.

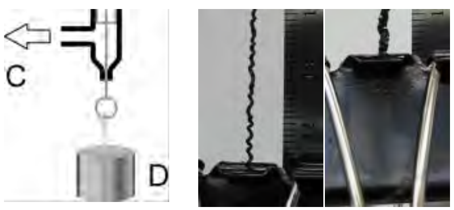
Realized Performance: (1) Higher contractile work capacity per cycle (2.5 kJ/kg) than expensive NiTi shape memory wires (0.93 kJ/kg). (2) Long cycle life, hysteresis-free performance, tensile strokes above 50%, and contractile power per weight 5X higher than for a car's engine. (3) Rotor rotation above 80,000 rpm.

CONTINUED: Results Overview for the AFOSR Project (4/15/2012 -4/14/2015) on "High Performance Artificial Muscles Using Twist-Spun Nanofiber and Hybrid Yarns"

3. New hybrid CNT yarn muscles driven by fast, liquid absorption/desorption (manuscript submitted and favorably reviewed by *Advanced Materials*)

a

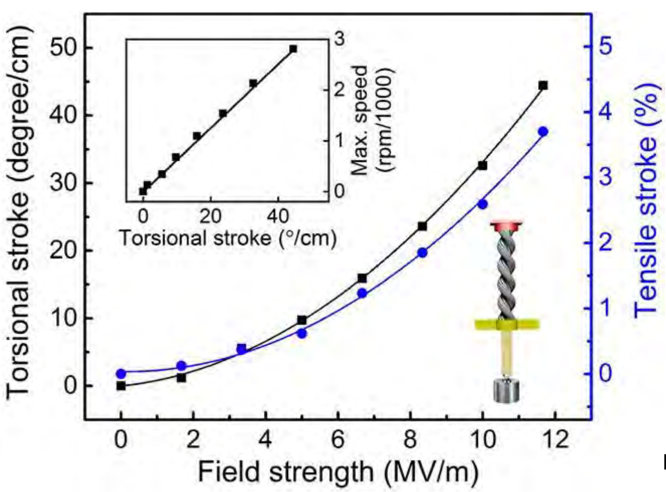
c



Mechanism: Volume change of silicone rubber guest in coiled CNT fiber drives solvation-powered tensile actuation.

Realized Performance: (1) Provides up to 50% stroke to generate 1.2 kJ kg^{-1} of mechanical energy during contraction, which dwarfs the 39 J kg^{-1} of natural muscle. (2) One Hz cycle rate demonstrated. (3) Based on measured work/cycle and the calc. energy needed to recycle fluids, the energy conversions is 16%. (4) Use: Harvestor of chemical energy of waste streams or as a powerful actuating sensor.

4. "Hierarchically Buckled Sheath-Core Fibers for Superelastic Electronics, Sensors, and Torsional Muscles" demonstrated and manuscript submitted to *Science*

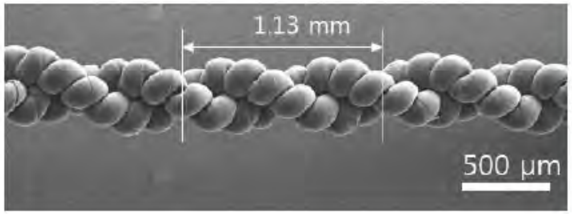


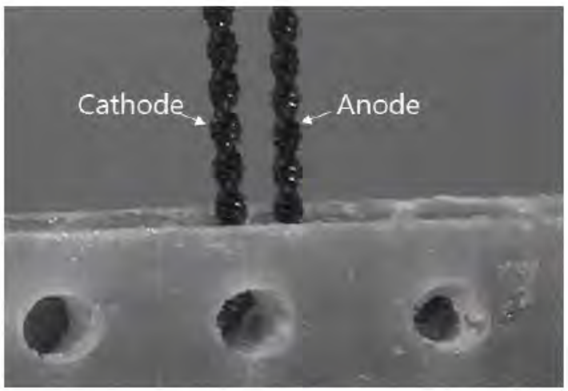
Materials Strategy: Novel 2-D periodically buckled CNT sheet sheaths on rubber fiber core are electrodes that enable giant stretch (up to 2470%) and giant twist insertion without significant conductance loss.

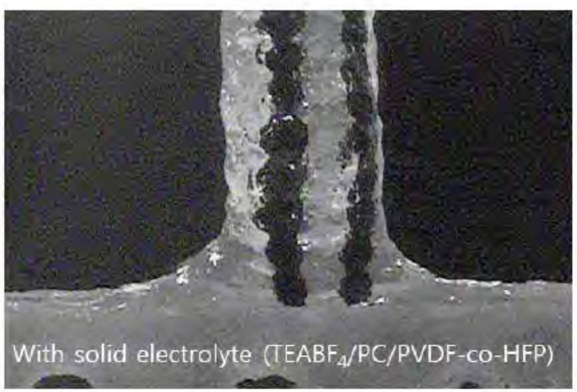
Torsional Actuator Mechanism & Performance: (1) Tensile actuation of rubber dielectric muscle layer in twisted fiber drives torsional actuation. (2) One hundred times higher torsional stroke per muscle length obtained than any prior-art electrically powered muscle that does not suffer from the limitations of thermal and electrochemical muscles.

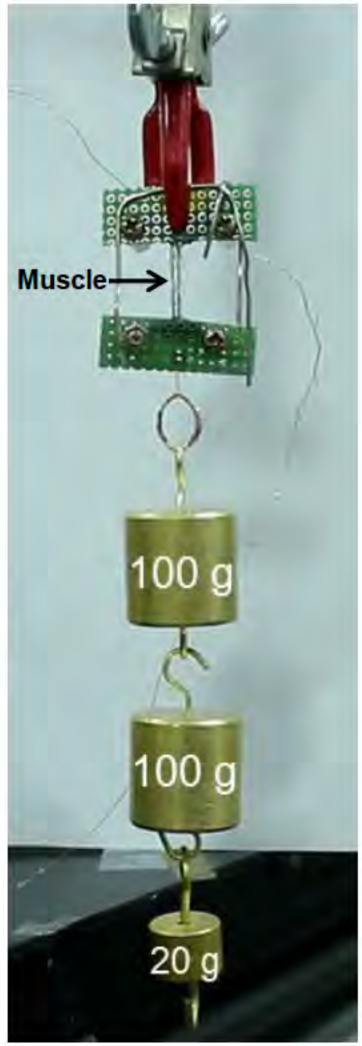
CONTINUED: Results Overview for the AFOSR Project (4/15/2012 -4/14/2015) on "High Performance Artificial Muscles Using Twist-Spun Nanofiber and Hybrid Yarns"

5. Yarn muscles converted to all-solid-state electrochemical muscles







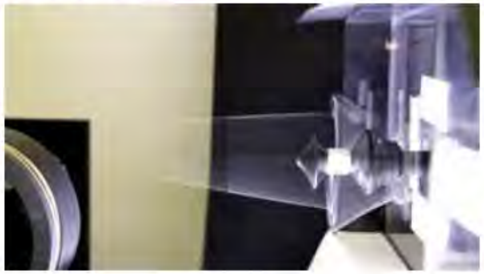


- ❖ In initial evaluations, obtained tensile strokes up to 24% and electrical-to-mechanical energy conversion efficiencies of up to 3.2%.
- ❖ These efficiencies already exceed the 1.5% that we obtain for pulse-actuated thermally-powered coiled muscles and the below 0.3% efficiencies of conducting polymer electrochemical actuators.
- ❖ In contrast with thermal muscles, the electrochemical muscles maintain stroke without significantly consuming energy.
- ❖ To increase efficiency and rate, we must (1) increase muscle work capacity per injected charge, (2) decease hysteresis in charge/discharge, (3) decrease energy losses in the electrolyte, and (4) decrease inter-electrode distance.

Additional results (2014) for the AFOSR Project on:

"High Performance Artificial Muscles Using Twist-Spun Nanofiber and Hybrid Yarns"

Continuous polymer muscle fabrication demonstrated and upscaled in summer 2014



100 m of coiled nylon yarn muscle

Polymer muscles used to quickly lift and lower a heavy weight (Marcio)

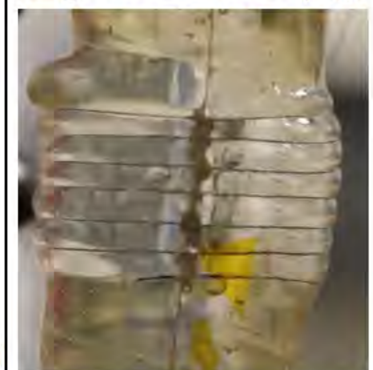
52 coiled, 65 lb test green-dyed polyethylene fishing lines provided the muscle, which was powered by alternating hot and cold water.

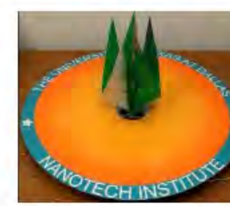
The diameter coiled muscle was 4 mm. The stroke was 5.5% as a 270 lb load was lifted. The maximum average power density realize for a polymer muscle during contraction was 7.1 horsepower/kg), 5X that of a car's engine.

Demonstrated diverse morphing structures:

❖ Textiles that change porosity for possible applications in comfort-adjusting clothing (project-derived US patent filed in 2015).

❖ A thermally powered composites of coiled silicone@CNT muscles in a silicone matrix provided a peristaltic pump (left), coiled nylon muscles in silicone matrix thermally morphed by torsional rotation to open and close a window or vent (middle), and torsional electro-thermal actuation morphed the 45 cm diameter logo structure (right).





❖ While we still have many results that need more comprehensive theoretical insights, our present theoretical work has importantly guided experiments and is described in our project publications and supplemental materials.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
13-08-2015	Final Performance	15-04-2012 to 14-04-2015

4. TITLE AND SUBTITLE
High Performance Artificial Muscles Using Twist-Spun Nanofiber and Hybrid Yarns

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-12-1-0211

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Ray Baughman

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF TEXAS AT DALLAS
800 W CAMPBELL RD
RICHARDSON, TX 75080 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTD

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The objective of this program was to develop new tensile and torsional artificial muscles that provide giant stroke, fast response, high force generation, and long cycle life while optimizing energy conversion efficiencies. During the program we extended thermal hybrid yarn muscles to fast muscles powered by liquid sorption/desorption by silicone guest. These muscles provide 50% stroke, 31X the work/cycle of natural muscles, 1 Hz cycle rate, and an energy conversion efficiency of up to 16%. We used these silicone/CNT yarn muscles as a control valve for liquid flow. We also demonstrated electrically powered dielectric polymer fiber muscles that generate 4.5% tensile stoke, 800 rpm torsional rotation speed, and 100X higher torsional stroke than any prior-art muscle that is non-thermal and non-electrochemical. These muscles are based on our project-developed super-elastic CNT sheath/rubber core conducting fibers that enable 2470% stretch and giant twist insertion without conductance loss. We further demonstrated allsolid-state electrically powered coiled CNT fiber muscles that generate 24% tensile stroke and provide 3.2% energy conversion efficiency (twice that of our CNT fiber muscles and 10X that of conducting polymer muscles). They maintain stroke without consuming significant energy. The publication of Artificial Muscles From Fishing Line and Sewing Thread (Science, 2014) generated TV, radio, and other world-wide news. In 2014, Lintec, Inc. started a laboratory close to UTD to commercialize CNT technology that we licensed and muscles technology for which we provided an option to license (world-wide patent nationalization

15. SUBJECT TERMS
Carbon Nanotube, Artificial Muscle, Twist-spun Nanotube Yearns, Shape Memory

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Ray Baughman
a. REPORT	b. ABSTRACT	c. THIS PAGE			
Unclassified	Unclassified	Unclassified	UU		19b. TELEPHONE NUMBER *(Include area code)* 972-883-6538

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

DISTRIBUTION A: Distribution approved for public release

1.

1. Report Type

F na Report

Primary Contact E-mail
Contact email if there is a problem with the report.

ray.baughman@utda as.edu

Primary Contact Phone Number
Contact phone number if there is a problem with the report

972-883-6538

Organization / Institution name

The Un vers ty of Texas at Da as

Grant/Contract Title
The full title of the funded effort.

H gh Performance Art f c a Musc es Us ng Tw st-Spun Nanof ber and Hybr d Yarns

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-12-1-0211

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Ray H. Baughman

Program Manager
The AFOSR Program Manager currently assigned to the award

Byung-L p Lee

Reporting Period Start Date

04/15/2012

Reporting Period End Date

04/14/2015

Abstract

The object ve of th s program was to deve op new tens e and tors ona art f c a musc es that prov de g ant stroke, fast response, h gh force generat on, and ong cyc e   fe wh e opt m z ng energy convers on eff c enc es. Dur ng the program we extended therma hybr d yarn musc es to fast musc es powered by   qu d sorpt on/desorpt on by s   cone guest. These musc es prov de 50% stroke, 31X the work/cyc e of natura musc es, 1 Hz cyc e rate, and an energy convers on eff c ency of up to 16%. We used these s   cone/CNT yarn musc es as a contro va ve for   qu d f ow. We a so demonstrated e ectr ca y powered d e ectr c po ymer f ber musc es that generate 4.5% tens e stoke, 800 rpm tors ona rotat on speed, and 100X h gher tors ona stroke than any pr or-art musc e that s non-therma and non-e ectrochem ca . These musc es are based on our project-deve oped super-e ast c CNT sheath/rubber core conduct ng f bers that enab e 2470% stretch and g ant tw st nsert on w thout conductance oss. We further demonstrated a -so d-state e ectr ca y powered co ed CNT f ber musc es that generate 24% tens e stroke and prov de 3.2% energy convers on eff c ency (tw ce that of our CNT f ber musc es and 10X that of conduct ng po ymer musc es). They ma nta n stroke w thout consum ng s gn f cant energy. The pub cat on of “Art f c a Musc es From F sh ng L ne and Sew ng Thread” (Sc ence, 2014) generated TV, rad o, and other wor d-w de news. In 2014, L ntec, Inc. started a aboratory c ose to UTD to commerc a ze CNT techno ogy that we   censed and musc es techno ogy for wh ch we prov ded an opt on to   cense (wor d-w de patent nat ona zat on

resu ted).

Distribution Statement

This is block 12 on the SF298 form.

D str but on A - Approved for Pub c Re ease

Explanation for Distribution Statement

If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form

Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF The maximum file size for an SF298 is 50MB.

SF298.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF . The maximum file size for the Report Document is 50MB.

FINAL REPORT FA9550-12-1-0211.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

1. “E ectr ca power from nanotube and graphene e ectrochem ca therma energy harvesters” T. J. Kang, S. Fang, M. E. Koz ov, C. S. Ha nes, N. L , Y. H. K m, Y. Chen, and R. H. Baughman, Advanced Funct ona Mater a s 22, 477-489 (2012).

2. "E ectr ca St mu at on of Pr mary Mur ne Myob asts on A gned Nanostructured Conduct ve Po ymer P atforms", A. Qu g ey, J. Raza , M. K ta, R. Ja , A. Ge m , A. Pen ngton, R Ova e-Rob es, R. H. Baughman, G. C ark, G. Wa ace, R. Kapsa, Advanced Hea thcare Mater a s 1, 801-808 (2012).

3. "Or ented Graphene Nanor bbon Yarn and Sheet from A gned Mu t -Wa ed Carbon Nanotube Sheets", J. Carretero–Gonzá ez, E. Cast o–Martínez, M. D. L ma, M. Ac k, D. M. Rogers, J. Sov ch, C. S. Ha nes, X. Lepró, M. Koz ov, A. A. Zhak dov, Y. Chaba , R. H. Baughman, Advanced Mater a s 24, 5695-5701 (2012).

4. “E ectr ca y, Chem ca y, and Photon ca y Powered Tors ona and Tens e Actuat on of Hybr d Carbon Nanotube Yarn Musc es”, M. D. L ma, N. L , M. Jung de Andrade, S. Fang, J. Oh, G. M. Sp nks, M. E. Koz ov, C. S. Ha nes, D. Suh, J. Forough , S. J. K m, Y. Chen, T. Ware, M. K. Sh n, L. D. Machado, A. F. Fonseca, J. D. W. Madden, W. E. Vo t, D. S. Ga vão, R. H. Baughman, Sc ence 338, 928-932 (2012).
5. “Yarn Supercapac tors for Text es and M crodev ces by B scro ng Conduct ng Po ymer Temp ated Carbon Nanotube Sheets”, J. A. Lee, M. K. Sh n, S. H. K m, H. U. Cho, G. M. Sp nks, G. G. Wa ace, M. D. L ma, X. Lepró, M. E. Koz ov, R. H. Baughman, S. J. K m, Nature Commun cat ons 4:1970 DOI: 10.1038/ncomms2970 www.nature.com/naturecommun cat ons (2013).
6. “Conduct ve funct ona b scro ed po ymer and carbon nanotube yarns”, S. H. K m, H. J. S m, M. K. Sh n, A Y. Cho , Y. T. K m, M. D. L ma, R. H. Baughman, S. J. K m, Roya Soc ety of Chem stry Advances 3, 24028-24033 (2013).

7. “Free-stand ng nanocompos tes w th h gh conduct v ty and extens b ty”, K.-Y. Chun, S. H. K m, M. K. Sh n, Y. T. K m, G. M. Sp nks, A. E. A ev, R. H. Baughman, and S. J. K m, Nanotechno ogy 24, 165401 (9 pp) (2013).

8. “Increas ng the eff c ency of thermoacoust c carbon nanotube sound projectors”, A. E. A ev, Y. N. Gartste n, R. H. Baughman, Nanotechno ogy 24, 235501 (11pp) (2013).

9. “Carbon Nanotube - Reduced Graphene Ox de Compos tes for Therma Energy Harvest ng App cat ons”, M. S. Romano, N. L , D. Ant ohos, J. M. Raza , A. Nattestad, S. Be rne, S. Fang, Y. Chen, R. Ja , G. G. Wa ace, R. H. Baughman, and J. Chen, Advanced Mater a s 25, 6602-6606 (2013).

10. “Art f c a Musc es from F sh ng L ne and Sew ng Thread”, C. S. Ha nes, M. D. L ma, Na L , G. M. Sp nks, J. Forough , J. D. W. Madden, S. H. K m, S. Fang, M. J. de Andrade, F. Göktepe, Ö. Göktepe, S. M. M rvak , S. Naf cy, X. Lepró, J. Oh, M. E. Koz ov, S. J. K m, X. Xu, B. J. Swed ove, G. G. Wa ace, R. H. Baughman, Sc ence 343, 868-872 (2014).

11. “Hybr d carbon nanotube yarn art f c a musc e nsp red by sp der s k drag ne”, K.-Y. Chun, S. H. K m, J. Park, M. K. Sh n, C. H. Kwon, Y. T. K m, G. M. Sp nks, R. H. Baughman, S. J. K m, Nature Commun cat ons 5:3322   DOI: 10.1038/ncomms4322 www.nature.com/naturecommun cat ons (2014).

12. “F ex b e Supercapac tor Made of Carbon Nanotube Yarn w th Interna Pores”, C. Cho , J. A. Lee , A. Y. Cho , Y. T. K m , X. Lepró, M. D. L ma , R. H. Baughman , S. J. K m , Advanced Mater a s 26, 2059-2065 (2014).

13. “H gh Power B ofue Ce   Text es from Woven B scro ed Carbon Nanotube Yarns”, C. H. Kwon, S.-H. Lee, Y.-B. Cho , J. A. Lee, S. H. K m, H.-H. K m, G. M. Sp nks, G. G. Wa ace, M. D. L ma, M. E. Koz ov, R. H. Baughman, S. J. K m, Nature Commun cat ons   5:3928   DOI: 10.1038/ncomms4928 www.nature.com/naturecommun cat ons (2014).

14. “A   So d State Carbon Nanotube Tors ona and Tens e Art f c a Musc es”, J. A. Lee, Y. T. K m, G. M. Sp nks, D. Suh, X. Lepró, M. D. L ma, R. H. Baughman and S. J. K m, Nano Letters 14, 2664-2669 (2014).

15. “Thermoacoust c exc tat on of sonar projector p ates by free-stand ng carbon nanotube sheets”, A. E. A ev, N. K. Mayo, R. H. Baughman, D. Av rov k, S. Pr ya, M. R. Zarnetske, J. B. B ottman, J. Phys. D: App . Phys. 47, 355302 (9 pp) (2014).

16. “Therma Management of Thermoacoust c Sound Projectors Us ng a Free-Stand ng Carbon Nanotube Aeroge Sheet as Heat Source”, A. E. A ev, N. K. Mayo, R. H. Baughman, D. Av rov k, S. Pr ya, M. R. Zarnetske, J. B. B ottman, Nanotechno ogy 25, 405704 (2014).

17. “Nanotube Aeroge Sheet F utter for Actuat on, Power Generat on, and Infrasound Detect on”, T. J. Kang, T. K m, E. Yun Jang, H. Im, X. Lepro-Chavez, R. Ova e-Rob es, J. Oh, M. E. Koz ov, R. H. Baughman, H. H. Lee, Y. H. K m, Sc ent f c Reports 4, 6105; DOI:10.1038/srep06105 (2014).

18. “F ex b e, U tra ght, Porous Superconduct ng Yarns Conta n ng She -Core Magnes um D bor de-Carbon Nanotube Nanof bers", J. S. Bykova, M. D. L ma, C. S. Ha nes, D. To y, M. B. Sa amon, R. H. Baughman, A. A. Zakh dov, Advanced Mater a s 26, 7510-7515 (2014).

19. “Tors ona Behav ors of Po ymer- nf trated Carbon Nanotube Yarn Musc es by Atom c Force M croscope”, C. H. Kwon, K. Chun, S. H. K m, J. Lee, J. K m, M. D. L ma, R. H. Baughman and S. J. K m, Nanosca e 7, 2489-2496 (2015).

20. “F ex b e, Stretchab e and Weavab e P ezoe ectr c F ber”, H. J. S m, C. Cho C. J. Lee, Y. T. K m, G. M. Sp nks, M. D. L ma, R. H. Baughman and S. J. K m, Advanced Eng neer ng Mater a s, 2015, DOI: 10.1002/adem.201500018.

21. “H gh performance e ectrochem ca and e ectrotherma art f c a musc es from tw st-spun carbon nanotube yarn”, J. A. Lee, R. H Baughman and S. J. K m, Nano Convergence 2015, 2:8 do :10.1186/s40580-014-0036-0.

22. “Eff c ent, Absorpt on-Powered Art f c a Musc es Based on Carbon Nanotube Hybr d Yarns”, M. D. L ma, W. Hussa n, G. M. Sp nks, S. Naf cy, D. Hagensash, J. S. Bykova, D. To y, and R. H. Baughman, Sma   2015, DOI: 10.1002/sm .201500424.

23. “Stab ty of carbon nanotube yarn b ofue ce n human body f u d”, C. H. Kwon, J. A. Lee, Y.-B. Cho , H.-H. K m, G. M. Sp nks, M. D. L ma, R. H. Baughman, S. J. K m, Journa of Power Sources 286, 103-108 (2015).

24. "Opt ca , e ectr ca , and e ectromechan ca propert es of hybr d graphene/carbon nanotube f ms", I. N. Kho manov, C. W. Magnuson, R. P ner, J.-Y. K m, A. E. A ev, C. Tan, T. Y. K m, A. A. Zakh dov, G. Sberveg er , R. H. Baughman, R. S. Ruoff, Advanced Mater a s, 2015, DOI: 10.1002/adma.201500785.

25. “H erarch ca y buck ed sheath-core f bers for supere ast c e ectron cs, sensors, and musc es”, Z. F. L u, S. Fang, F. A. Moura, J. N. D ng, N. J ang, J. D , M. Zhang, Xav er Lepró, D. S. Ga vão, C. S. Ha nes, N. Y. Yuan, S. G. Y n, D. W. Lee, R. Wang, H. Y. Wang, W. Lv, C. Dong, R. C. Zhang, M. J. Chen, Q. Y n, Y. T. Chong, R. Zhang, X. Wang, M. D. L ma, R. Ova e-Rob es, D. Q an, H. Lu, R. H. Baughman, Sc ence, n press (2015).

Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Start ng FY	FY+1	FY+2
Sa ary			
Equ pment/Fac t es			
Supp es			
Tota			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Ju 13, 2015 19:23:25 Success: Ema Sent to: ray.baughman@utda as.edu