

Multi-Functional Materials Interdisciplinary Research Theme 2018 Year End Report



2018 Multi-Functional Materials IRT Annual Report

IRT Scope and Mission

The Multi-Functional Materials (MFM) IRT aims to develop major research collaborations amongst faculty across CEAS, and with participation from A&S faculty, that define CU Boulder as a leader in the field. A "multifunctional material" is loosely defined as one that has some combination of sensing, computation, and actuation functionality, which allows adaptive and real time response to the material's environment. However, the definition is intended to be a broad one, and various other aspects fall under the MFM IRT umbrella, including:

- Materials capable of a combination of sensing, computation, actuation, and/or power generation and storage functionalities
- Integration of materials into systems with innovative, emergent behaviors, i.e. more than the sum of their parts
- Biological and bio-inspired materials and systems that exhibit the above behaviors
- Development of advanced fabrication and characterization strategies for the above

A key point is that the multiple functionalities are carried out in the material or material system in a non-trivial way, such that they are intrinsic to the design, e.g. embedded logic. Another viewpoint is that the complexity that normally hinders the development of advance materials will instead be harnessed to turn subtle fundamental behaviors into robust engineering systems. A few examples of application areas include: soft and hybrid robotics, human prosthetics and assistive devices, bioelectronics, smart textiles, smart buildings, and drones and UAV's.

The mission of the MFM IRT is to advance CU as a field-defining leader and epicenter of research in these areas. It will nucleate multi-PI activities that have substantial opportunity to lead to full center-scale efforts, which will pull together faculty from diverse research areas into cohesive yet flexible and dynamic teams.

Most Significant IRT Accomplishments in 2018

- Christopher Keplinger and colleagues were awarded \$2M from the NSF EFRI program for a project on <u>An End-To-End Framework For Soft Robot Design And Control Based On High-Performance</u> <u>Electrohydraulic Transducers</u>. Keplinger's work on Hydraulically amplified self-healing electrostatic actuators appears in <u>Newsweek</u>, <u>National Geographic</u>, <u>Tech Times</u>, <u>Science Daily</u>, and elsewhere.
- Nikolaus Correll advised NSF program managers on the creation of a new NSF Designing Materials to Revolutionize and Engineer our Future (DMREF) solicitation, which includes a section on "robotic materials" that was inspired by the <u>workshop</u> that Correll organized.

- He was also the General Chair of the <u>2018 Symposium on Distributed Autonomous Robotic</u> <u>Systems</u>, held here on campus.
- Sean Humbert and colleagues were awarded \$4.5M to support its participation in the <u>Subterranean Challenge</u>.
- Gregory Whiting and collaborators were awarded a \$1.7M award from DARPA for a project on <u>Precision Agriculture using Networks of Degradable Analytical Sensors (PANDAS)</u>.
- Daniel Dessau (Physics), Charles Musgrave (ChBE), Sean Shaheen (ECEE) and colleagues from the Physics and Chemistry Departments were award \$1M from the Keck Foundation for a project on <u>High Temperature Superconductivty in Organic Solids</u>.

Seed Grant Summary

- Proximity, Contact, and Force Sensing Prosthetic Finger Tip Material for DARPA HAPTIX Program (PI: Jacob Segil and Richard Weir (Anschutz))
- Smart-Particle Adhesives (PIs: Yifu Ding, Jialiang Xiao, Rong Long)
- Power for multi-functional materials systems and soft robotics: a survey (PIs: John Pellegrino, Robert McLeod, Hanh-Phuc Le)
- A Self-Normalizing, Adaptive, Pneumatic (SNAP) Approach to Lower Limb Amputee Care (PIs: Mark Rentschler, Dr. Noel So (Veteran Affairs Hospital))
- Prototyping Support for Multi-Functional Textiles Research (PIs: Laura Devendorf, Allison Anderson)
- Clothing with Wireless Powering (PIs: Zoya Popovic, Khurram Afridi)
- Integrated stretchable heating circuits and liquid crystal elastomers for soft robotics and artificial muscles (PIs: Jianliang Xiao, Kai Yu (CU Denver))
- Evaluation of Mechanochemical Bond Breakages at the Edges of Soft Hydrogels (PIs: Andrew Goodwin, Christopher Bowman, Rong Long)
- Self-organized Mechanical Load Bearing in Bee Swarms: 3D Structure Reconstruction via X-ray (PIs: Orit Peleg, Franck Vernerey)
- Support to join the NextFlex Manufacturing Institute (PIs: Gregory Whiting, Christoph Keplinger, Sean Shaheen, Jianliang Xiao)
- Mesoscale model development for multi-interface materials (PIs: Sanghamitra Neogi, Jed Brown)
- Multifunctional electronic skins for applications in prosthetics and spacesuits (PIs: Jianliang Xiao, Wei Zhang, Allison Anderson, Jacob Segil)
- Living Building Materials for Regenerative Architecture (PIs: Wil Srubar, Gregor Henze, Ginger Ferguson)
- Smart, Strain-Sensing Structures Inspired by Bone (PIs: Ginger Ferguson, Sean Humbert, Gregory Whiting)

- Functional Microbubble Swarms: Theory and Experiment (PIs: Mark Borden, Franck Vernerey, Orit Peleg)
- Leveraging Novel Tactile Robotic Materials to Solve Molyneux's Problem (PIs: Bradley Hayes, Christoffer Heckman)
- Development of Artificial Muscles for Prosthetic Devices using Hydraulically Amplified Selfhealing Electrostatic (HASEL) Actuators (PIs: Jacob Segil, Chrisoph Keplinger)
- Wireless Active Bandages (PIs: Richard Han, Tam Vu, Gregory Whiting)

Next Steps and Anticipated Milestones

Planned activities include regular meetings and workshops for the MFM faculty, for the purpose of continually generating new ideas for research directions and funding opportunities and to brainstorm on solutions to specific problems. These meetings will take several forms. For instance, a given meeting may be aimed at a specific research topic, and faculty from broad backgrounds will be asked to brainstorm on approaches from their perspective. This will be done in small-group breakout session followed by report-outs to the group. Key faculty from other universities may also be invited. Another method of structuring the meetings will follow a Google X strategy, in which someone proposes a solution to a big-picture problem, and it is the tasks of others in the room to find any flaws in the formulation of the problem or its solution. (At Google X it is considered a success if someone can find a crucial reason to kill a large project, especially early on.)

A key area of emphasis will be development of relationships with program managers at federal funding agencies. This is necessary to be aware of and in fact shape long-term funding opportunities. Target agencies include DARPA, Army Research Labs, Air Force Research Labs, Dept. of Energy, and the National Science Foundation. To encourage these activities, the MFM will fund travel of PI's to visit program managers or to host them here for small meetings when possible. We will also make strong use of the resources provided by Lewis Burke Associates. Shaheen has recently taken advantage of this resource by visiting Army Research Labs as arranged by Dr. Reed Skaggs of Lewis Burke, and several follow-up activities have resulted.

In addition to the regular meetings and workshop on campus, we will organize one or more larger conferences that pull in researchers from across the U.S. At present we are in the planning stages for a conference on Neuromorphic Materials and Systems to be held in Boulder in the fall of 2019. It will be co-organized with Prof. Alberto Salleo from Stanford and will include representatives from Army Research Labs. Dr. Paul Lane in the NSF division of Electronic, Photonic, and Magnetic Materials has tentatively committed to funding graduate student support for the meeting.

IRT Performance Metrics

Industry Collaboration

New external collaborations

- <u>Dr. Thomas Cooley</u>, Chief Scientist at Air Force Research Laboratory, toured campus on August 6 and met with MFM faculty Sean Humbert, Timothy White, and Sean Shaheen to discuss potential collaborations.
- Shaheen visited Army Research Labs and held meetings with Dr. Paul Pellegrino, Branch Chief for Optics & Photonics Integration, and Dr. Christopher Morris, Branch Chief for Micro/Nano Materials. Discussion of collaborative efforts and conference organizing on neuromorphic materials and systems were held, and a follow-up visit is planned.
- Nikolaus Correll advised NSF program managers on the creation of a new NSF Designing Materials to Revolutionize and Engineer our Future (DMREF) solicitation, which includes a section on "robotic materials" that was inspired by the <u>workshop</u> that Correll organized.
- Richard Han and Nikolaus Correll have interacted with DARPA and are helping to organize a conference on Autonomous Proprioceptive Actuators for Injury Neutralization (A-PAIN), motivated by their work on Active Bandages for rapid wound healing.
- Shaheen has had preliminary discussions with <u>Dr. Paul Lane</u> at the NSF to advise on the creation of an EFRI program on neuromorphic devices, to be released in 2019 if selected by NSF management.
- Shaheen has arranged discussions with <u>Dr. Shawn Walsh</u> of the Army Research Lab. He has expressed interest in expanding collaborations in the public sector.
- Shaheen has arranged meetings with representatives of 3M Corporation to discuss potential collaborations and sponsored research opportunities. In attendance from 3M will be Dr. Daniel Snustad, Global Technical Director of the Corporate Research Materials Laboratory (CRML), Dr. Philip Clark, Technical Director of CRML, and Dr. Mark Strobel, Corporate Scientist in their Corporation Research Process Laboratory.

Technology transfer, IP generation, and start-ups

- Patent Application US20180153631A1 on Multifunctional operational component for robotic devices was published by Mark Rentschler.
- Patent Application US9909814B2 on Flexible thermal ground plane and method for manufacturing the same was published by Ronggui Yang.
- Patent Application US20180066132A1 on Conductive polymeric compositions and applications was published by Shaheen and Robert McLeod.
- Patent Application US20180306218A1on Complex Stress-Engineered Frangible Structures was published by Gregory Whiting and colleagues.
- Patent Application US20180252659A1on Printed Gas Sensors was published by Gregory Whiting and colleagues.

Reputation

Faculty in national leadership positions

- A workshop on <u>Robotic Materials</u> was organized by Nikolaus Correll at the Keck Center in Washington D.C. in April 2018. It was hosted by the Computing Community Consortium. Correll wrote a summary of the workshop on <u>CCC Blog</u>.
- Nikolau Correll was the General Chair of the <u>2018 Symposium on Distributed Autonomous</u> <u>Robotic Systems</u>, held here on campus.
- Nikolaus Correll wrote an article on <u>Robotics Getting a Grip on General Manipulation for IEEE</u> <u>Spectrum</u>.
- Robert MacCurdy was names as Associate Editor for the Journal of 3D Printing and Additive Manufacturing.

National press for IRTs

- Christopher Bowman's work on Programmable, fully reversible shape-switching material appeared in <u>Science Daily</u> and <u>phys.org</u>.
- Jian Liang Xiao's work on Lightweight, strong, and super thermally insulating nanowood appeared in <u>phys.org</u>.
- Christoph Keplinger's work on Hydraulically amplified self-healing electrostatic actuators appears in <u>Newsweek</u>, <u>National Geographic</u>, <u>Tech Times</u>, <u>Science Daily</u>, and elsewhere.
- Students working with Nikolaus Correll's company Robotics Materials, Inc. won the President's Award from the Japanese Society of Mechanical Engineers.
- Sean Humbert's was interviewed on Colorado Public Radio's program Colorado Matters, for his work the DARPA Subterranean Challenge. The interview can be found <u>here</u>.

Recognition by peer institutions

• Major research awards below included collaborations with colleagues at Cornell University, Carnegie Mellon University, and Jet Propulsion Laboratory, among others.

Proposals and Projects

Multi-department proposals/projects (> \$1M)

- Christopher Keplinger and colleagues were awarded \$2M from the NSF EFRI program for a project on <u>An End-To-End Framework For Soft Robot Design And Control Based On High-Performance</u> <u>Electrohydraulic Transducers</u>.
- Sean Humbert and colleagues were awarded \$4.5M to support its participation in the <u>Subterranean Challenge</u>.
- Gregory Whiting and collaborators were awarded a \$1.7M award from DARPA for a project on <u>Precision Agriculture using Networks of Degradable Analytical Sensors (PANDAS)</u>.
- Gregor Henze and team were awarded a \$2M award from ARPA-E for a project on <u>Battery-free</u> <u>RFID sensor network for human presence sensing</u>. The award was announced by Colorado U.S. Senators Michael Bennet and Cory Gardner (<u>here</u>) and was publicized by <u>NREL</u>.

• Daniel Dessau (Physics), Charles Musgrave (ChBE), Sean Shaheen (ECEE) and colleagues from the Physics and Chemistry Departments were award \$1M from the Keck Foundation for a project on High Temperature Superconductivty in Organic Solids.

Center-scale proposals/projects (> \$10M)

• None to date

APPENDIX IRT Members

Last Name	First Name	Dept	Email
Appelo	Daniel	APPM	daniel.appelo@colorado.edu
Anderson	Allison	AES	allison.p.anderson@colorado.
Borden	Mark	ME	mark.borden@colorado.edu
Bowman	Christopher	ChBE	christopher.bowman@colorado.edu
Cha	Jennifer	ChBE	jennifer.cha@colorado.edu

Chen	Xudong	ECEE	xudong.chen@colorado.edu
Correll	Nikolaus	CS	nicolaus.correll@colorado.edu
Ding	Xiaoyun (Sean)	ME	xiaoyun.ding@colorado.edu
Ding	Yifu	ME	yifu.ding@colorado.edu
Ferguson	Virginia	ME	virginia.ferguson@colorado.edu
Frew	Eric	AES	eric.frew@colorado.edu
Goodwin	Andrew	ChBE	andrew.goodwin@colorado.edu
Han	Richard	CS	richard.han@colorado.edu
Heckman	Christoffer	CS	christoffer.heckman@colorado.edu
Henze	Gregor	CEAE	daven.henze@colorado.edu
Herzfeld	Ute	ECEE	ute.herzfeld@colorado.edu
Holder	Aaron	ChBE	aaron.holder@colorado.edu
Humbert	James "Sean"	ME	sean.humbert@colorado.edu
Hussein	Mahmoud	AES	mih@colorado.edu
Kaar	Joel	ChBE	joel.kaar@colorado.edu
Kapteyn	Henry	PHYS	henry.kapteyn@colorado.edu
Keplinger	Christoph	ME	christoph.keplinger@colorado.edu
Le	Hanh-Phuc	ECEE	hanhphuc@colorado.edu
Lee	Se-Hee	ME	leeyc@colorado.edu
Long	Rong	ME	rong.long@colorado.edu
Lv	Christine	CS	qin.lv@colorado.edu
MacCurdy	Robert	ME	robert.mcleod@colorado.edu
Maute	Kurt	AES	kurt.maute@colorado.edu
McLeod	Robert	ECEE	robert.mcleod@colorado.edu
Medlin	Will	ChBE	will.medlin@colorado.edu
Neogi	Sanghamitra	AES	sanghamitra.neogi@colorado.edu
Neu	Corey	ME	cpneu@colorado.edu
Рао	Lucy	ECEE	lucy.pao@colorado.edu
Park	Wounjhang	ECEE	wounjhang.park@colorado.edu
Peleg	Orit	CS	orit.peleg@colorado.edu
Pellegrino	John	ME	john.pellegrino@colorado.edu
Pourahmadian	Fatemeh	CEAE	fatemeh.pourahmadian@colorado.edu
Raj	Rishi	ME	rishi.raj@colorado.edu
Raschke	Markus	PHYS	markus.raschke@colorado.edu
Rentschler	Mark	ME	mark.rentschler@colorado.edu
Segil	Jacob	EPLUS	jacob.segil@colorado.edu
Schwartz	Daniel	ChBE	daniel.schwartz@colorado.edu
Shaheen	Sean	ECEE	sean.shaheen@colorado.edu
Shang	Li	ECEE	li.shang@colorado.edu
L		I	

Srubar	Wil	CEAE	wil.srubar@colorado.edu
Trivedi	Ashutosh	CS	ashutosh.trivedi@colorado.edu
Vernerey	Franck	ME	franck.vernerey@colorado.edu
White	Timothy	ChBE	timothy.j.white@colorado.edu
Хіао	Jianliang	ME	jianliang.xiao@colorado.edu
Yang	Ronggui	ME	ronggui.yang@colorado.edu