Wearable and Stretchable Electronic Devices

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Message from PITA Co-Directors

The Pennsylvania Infrastructure Technology Alliance (PITA) has connected Pennsylvania’s companies with the Commonwealth’s world-class university researchers and their students for over 20 years, promoting economic development in Pennsylvania. PITA, which is funded by the Commonwealth of Pennsylvania’s Department of Community and Economic Development, helps Pennsylvania increase the state’s market competitiveness through the development of new technologies and process improvements.

We are proud of the program’s strong history of working with Pennsylvania companies and students to foster economic growth in the state. The program has supported over 1,235 technology and process improvement projects in partnership with more than 490 Pennsylvania companies, obtaining more than $2 of funding from industry and federal resources for every $1 of state funding obtained. PITA has also mobilized more than 470 faculty members and 2,060 students to work on Pennsylvania-specific technology, process improvement, and educational outreach projects, and has also enabled 15 startup companies created from PITA-sponsored technologies. In this edition of the PITA Newsletter, we highlight recent partnerships with Liquid X, Precision Neuroscopics, Buzzi Unicem, and Dynalene Inc.

As always, we welcome partnerships with new companies. Those interested in working with faculty and graduate students on short-term technology development or process improvement projects should contact the PITA Associate Directors Chad Kusko, Lehigh University, chk205@lehigh.edu; or Colleen Mantini, Carnegie Mellon University, cmantini@cmu.edu.
Wearable and Stretchable Electronic Devices

A 2016 PITA project has led to commercially viable, soft-matter printed electronics for wearable health monitoring. The thin and adhesive wearable technology has an artificial second-skin or Band-Aid like physical form, so users will hardly even notice that they’re wearing the sleek devices. These devices can track users’ activity and vital signs like body temperature, pulse, and respiration rates continuously, outside of healthcare facilities. As a result, these technologies could play a crucial role in the early diagnosis of serious health conditions that are typically difficult to catch, like atrial fibrillation.

A group led by Carmel Majidi and Burak Ozdoganlar, professors of mechanical engineering at Carnegie Mellon University, teamed up with Liquid X, a Pittsburgh-based startup company. Liquid X manufactures metal ink technologies, and this collaboration expanded upon an existing relationship, accelerating Majidi and Ozdoganlar’s research into a commercially viable product.

“The goal was to leverage our existing relationship with Liquid X. We set out to develop scalable manufacturing methods for creating electronics that are not only flexible, but also stretchable and could be incorporated into clothing and garments, or even just directly on the skin,” Majidi says.

Majidi’s research group, the Soft Machines Lab, has generally focused on soft and stretchable electronics that are compatible with human skin. Instead of using rigid metal wiring, they’re using a metal alloy made up of indium and gallium that remains as liquid at room temperature, essentially exhibiting properties of non-toxic mercury. This liquid wiring is housed within small, microscopic channels inside a silicone rubber and is used to wire together the same transistors, microprocessors, and power regulators found on a circuit board in a smartwatch. But instead of a rigid and bulky watch, this technology is bendable, stretchable, and waterproof.

The liquid wiring allows the soft devices to stretch to over twice their natural length, making it perfect for wearable health monitoring, including measuring the user’s heart rate, blood-oxygen levels, and muscle and nervous system activity.

“We really focused on developing a scalable manufacturing process for the technology during this PITA project,” says Kadri Bugra Ozutemiz, a former team member co-supervised by Majidi and Ozdoganlar who recently completed his Ph.D. “We developed the skeleton of this fabrication flow — we figured out a way both to mass fabricate the liquid metal circuit boards and to integrate chips with these liquid metal circuit boards to make them fully functional. The circuits are stretchable and soft at the same time. They consistently work under deformation without failure.”

“We had already demonstrated these capabilities in the lab, so we knew it was possible,” Ozutemiz says. “We’re still using similar materials as we did in the lab, but the manufacturing processes and sub-process that resulted from this project have made the technology overall more scalable, commercially viable, and high throughput.”

During the course of this project, the team successfully filed a patent application for the technology’s material architecture, as well as the processing and manufacturing of liquid metal. “We were very careful to work with techniques that didn’t just work in the lab under controlled conditions; we wanted this process to work in more of a factory setting,” Majidi says. Along with wearable health monitoring, the numerous future applications could include motion capture technology, too, replacing bulky data gloves and sensor suits.

By Jacob Williamson-Rea

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— Carmel Majidi, Carnegie Mellon University, professor of mechanical engineering
After a traumatic head injury or stroke, the brain can undergo what researchers call a "brain tsunami." The traumatized brain reacts with a period of hyperactivity, followed by a period of inactivity. Technically referred to as a cortical spreading depolarization (CSD), a brain tsunami moves like a powerful and slow wave across the brain surface. This complex phenomenon has emerged as one of the most reliable indicators of severity of an initial injury, but the tsunami itself can also cause further damage. As part of a vicious feedback loop, the intense spikes of hyperactivity and inactivity can further damage cells, worsening the brain’s condition beyond the initial trauma.

A research team led by Carnegie Mellon University, in collaboration with clinicians at the University of Pittsburgh, is exploring how to detect and minimize additional brain damage. They paired up with Precision Neuroscopics, a Pittsburgh-based startup company, as part of a 2018 PITA project.

“I think detection of worsening brain injuries is a hugely important problem, with no existing solution that actually works,” says Pulkit Grover, associate professor of electrical and computer engineering at Carnegie Mellon University. “Detection of brain tsunamis, and their subsequent suppression, could be a game-changer.”

“We had been exploring electroencephalogram technologies in general, mostly focusing on sensing brain signals noninvasively,” says Shawn Kelly, co-founder of Precision Neuroscopics.

An electroencephalogram (EEG) measures the brain’s electrical activity and ideally could be used to evaluate the extent of an injury. The Carnegie Mellon and Precision Neuroscopics team wanted to do more than just measure the brain’s electrical activity — they wanted to detect brain tsunamis.

Grover, Kelly, and Ashwati Krishnan, a postdoctoral researcher at Carnegie Mellon’s Center for the Neural Basis of Cognition, set out to detect brain tsunamis, along with other researchers in Grover’s lab.

“We are designing the algorithms for detecting brain tsunamis,” Grover says. “The techniques I’m exploring include machine learning and signal processing, and I’m also working closely with clinicians to understand their end goals.” This work is led by Ph.D. student Alireza Chamanzar in Grover’s lab.

Meanwhile, Krishnan has been refining the conductive sponge technology, which allows the researchers to administer EEG recordings noninvasively — and at a lower cost than traditional EEG technologies.

“Typically, when researchers use sensors to measure brain activity, they use an electrode gel, which contains ions,” says Krishnan. “The gel allows the brain and the sensors to ‘talk’ to each other.” However, electrode gels are costly, require extensive setup, and ultimately do not provide a high enough spatial resolution of EEG for detecting additional post-injury damage.

“Ashwati [Krishnan] brought in her drive for low-cost, high-quality biomedical diagnosis and treatment systems,” Grover says. “The entire idea of conductive sponges is her idea, from conceptualization, to design and implementation. She mentored an extremely capable CMU undergraduate, Kalee Rozylowicz, who is now planning to pursue graduate school. Both are co-authors on the primary publications resulting from this work.”

Krishnan says that the partnership with Precision Neuroscopics is crucial in the scaling of their technology, and that partnerships like these are important across the entire field in general.

“I believe that engineering is a field where you can’t just prove that something works once in a research lab,” she says. “Engineers need to think about applying technology, because engineering shines when people actually use it. I appreciate this relationship with Precision Neuroscopics because there is an immediate possibility for taking what we do in the lab and then directly translating that to a larger scale.”

“Precision Neuroscopics have been amazing collaborators,” Grover says. “They helped us set up an entirely new lab, provided us feedback and expertise at various stages, and it was great to see Pittsburgh graduates find jobs at Precision Neuroscopics, including some from our lab.”

“The successful PITA partnership led to increased funding,” Grover says. Including a DARPA award of about $2.4 million, as well as a grant from the Center for Machine Learning and Health at Carnegie Mellon University, which will be used to further develop and refine the technology.
Manufacturing the Impossible with Cement: New Shapes Beyond Formwork

By Amanda Allekotte

Through the support of the Pennsylvania Department of Community and Economic Development’s PITA program, cement manufacturer Buzzi Unicem USA and Lehigh University have established a strategic partnership spanning research, recruitment, outreach, and cultural activities. Buzzi Unicem, which brings in billions of dollars in annual revenue, has a footprint spanning 13 countries and three continents. Its largest branch by profit, Buzzi Unicem USA, is headquartered in Bethlehem, Pa., close to Lehigh University. The Lehigh/Buzzi Unicem partnership aims to develop research projects that, in the future, will facilitate establishing a U.S.-based Buzzi Unicem R&D department that complements the company’s existing R&D departments in Italy and Germany.

The collaboration’s flagship project focuses on developing a new methodology for 3D printing concrete components and structures. The most common techniques for 3D printing concrete consist of extruding premixed low-slump concrete through a large nozzle attached to a robotic arm. While this approach was instrumental in popularizing concrete 3D printing and led to the first simple 3D printed structures, it has several drawbacks. Mainly, the process deposits subsequent layers, one over the other, with the previous layers supporting the new ones. This layering prevents the creation of openings and overhangs. The resulting surfaces have visible layers, which some consider less aesthetically pleasing.

To address these drawbacks, Lehigh and Buzzi Unicem are pioneering a technique that consists of precisely jetting microdroplets of a water-based liquid on extremely thin layers of cement and fine aggregates. The printer automatically spreads layer after layer of the dry mix, and the automated print-head selectively activates the cement hydration in the locations that are needed for that layer by jetting droplets only in those regions. The inert cement and aggregates serve as support for the following layers, allowing the creation of openings, cavities, and overhangs. At the end of the printing process, the dry mix that did not react is easily collected and reused.

The process is completely automated and free from the constraints of traditional manufacturing.

“Effectively, free-form concrete with free-form reinforcement will constitute a new construction material. This will require a new design paradigm and leverages a modern, efficient, and sustainable manufacturing process.”

— Dr. Paolo Bocchini, Lehigh University

For more information, contact Paolo Bocchini, Lehigh University, pab409@lehigh.edu.

By Amanda Allekotte

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By Sudhakar Neti, Amanda Allekotte

As renewable energy technologies continue to replace fossil fuel power plants, solar energy is expected to play an increasing role in the nation’s energy future. The U.S. Department of Energy has identified the need to improve performance and cost-effectiveness of Generation 3 Concentrated Solar Power Systems (Gen3 CSP). Thermal energy storage (TES) is one area where further research is expected to lead to advancements toward this goal, given the intermittent generation associated with solar energy.

Dynalene Inc., a Lehigh Valley-based heat transfer fluid and coolants company, and Lehigh University’s Energy Research Center teamed up to explore the use of chloride salts for TES to increase efficiency and lower the levelized cost of energy (LCOE) for Gen3 CSPs. Solar power generation requires good heat transfer fluids and media for efficient energy storage, and the team identified that, compared to the more commonly used nitrate-based solar salts, the low cost and high thermal stability (>700ºC) of inorganic chloride salt blends make these blends excellent candidates for Gen3 CSP.

However, chloride salt blends are known for being corrosive and having poor thermal conductivity. Through prior PITA and National Science Foundation funding, the Dynalene-Lehigh team addressed this issue of corrosiveness by developing a patent-pending inhibited molten chloride salt (phase change medium “PCM” chloride salt), which provides corrosion resistance to stainless steel. For this 2019–2020 PITA project, the team sought to solve the issue of poor thermal conductivity by embedding PCM chloride salts into the pores of thermally conductive graphite foams to create a graphite foam-chloride salt composite that is ideal for high temperature TES applications.

Graphite foam is a highly porous, thermally stable carbon-based material with high thermal conductivity and tolerance to salts. By embedding a chloride salt into the porous structure of the foam, the graphite provides additional heat transfer surface area for the salt, which reduces the overall system-level costs by increasing the effective thermal conductivity of the foam and salt composite. Infiltration of the graphite foams was performed with high temperature binary- and ternary-inhibited chloride salt mixtures above the melting temperature of the salt, under pressurized and high purity inert nitrogen gas conditions, into evacuated graphite foams using an apparatus designed by the team (see Figure 1a-1c). Before and after infiltration, Dynalene performed characterization of the carbon/graphite foams using Scanning Electron Microscopy and Energy Dispersive X-Ray Spectroscopy. Figure 2a-2c shows representative images of successful infiltration.

The team includes Dr. Carlos Romero, Dr. Alp Oztekin, Dr. Nasser Vahedi, Dr. Sudhakar Neti, Mr. Hao Lan, and Mr. Huazhi Chen from Lehigh University and Dr. Sreya Dutta, Dr. Satish Mohapatra, and Mr. Michael Nappa from Dynalene. Dr. Neti, one of the project’s principal investigators, says that the team is grateful for the financial support provided by PITA and Dynalene for this project and hopes to continue research in this area. “Additional work is underway to fully characterize the graphite foam-chloride salt composite,” Neti says. “The project stands to impact the rapidly expanding TES field, where improvements in thermal properties of materials can have significant economic advantages.”

In the future, commercialization of the graphite foam-chloride salt composite is expected to help position Pennsylvania as a leader in the new energy landscape.
Manufacturing the Impossible with Cement

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formwork, which also enables manufacturing geometries that could not be formed with traditional casting. The geometric precision is millimetric and the smooth surface finish results in manufactured objects with a more appealing look. Ultimately, the new technique increases the sustainability of cement construction by allowing for material to be used only in regions of the structural components where it will be most effective—a goal that is easily achieved by metal structures, but much more difficult to achieve with traditional formwork. The ability to reuse all the cement powder that did not react during the 3D printing process also contributes to the overall sustainability of the process.

The team includes Dr. Paolo Bocchini, Dr. John Fox, and Dr. Clay Naito, as well as students Joseph Ingaglio, Xingjian Wang, and Trevor Belinsky from Lehigh University. The Lehigh team members work with several scientists and engineers from Buzzi Unicem, coordinated by Michele Maranzana, vice president of Manufacturing Processes. To develop the new process, the team first focused on developing an effective manufacturing protocol and selecting the appropriate materials. After a broad range of tests, Buzzi Unicem’s CSA cement emerged as the best option for the binder, due to its fast set time (which confers strength during the printing process), ability to rapidly absorb water (which prevents water from “bleeding” into locations where hydration should not occur), and ability to preserve geometric accuracy.

The results obtained with Buzzi Unicem’s CSA cement were recently published in Construction and Building Materials, a prestigious international journal, and will serve as the starting point for developing a specific 3D printing cement mix that Buzzi Unicem USA may bring to market. The team is currently aiming to increase the size of produced objects by using larger printers and modular printing of components assembled with post-tensioning cables. The team is also investigating a novel way of applying reinforcement with the same geometric freedom that 3D printing offers to concrete. Another goal is to develop a new design paradigm that embraces this unprecedented geometric freedom not only for architectural decoration, but also for structural optimization. To this end, the team is investigating techniques for topology optimization.

While the methodology is not yet ready to be deployed in practice, it has the potential to revolutionize both the precast industry and the entire construction sector. “Effectively, freeform concrete with freeform reinforcement will constitute a new construction material,” Bocchini says. “This will require a new design paradigm and leverages a modern, efficient, and sustainable manufacturing process.” “New shapes that do not need formwork will enable visionary designs and cost savings,” Maranzana says.
PITA is an **industry-led program** that enables companies to identify opportunities for the university, through its faculty and students, to provide expertise and capabilities that they may not otherwise be able to access.

Pennsylvania companies gain access to **faculty expertise, university equipment, and students**. University faculty and students are afforded the opportunity to work on **real-world, market-driven challenges** confronting Pennsylvania companies.

Faculty and students assist companies in creating technology of the future and enhancing the competitiveness of Pennsylvania companies with the goal of the creation of jobs in Pennsylvania and the retention of highly trained/educated students in Pennsylvania.

PITA Technology Focus Areas include:

- Transportation
- Telecommunications and Information Technology
- Facilities
- Water Systems
- Energy & Environment
- Public Health & Medicine
- Hazard Mitigation & Disaster Recovery

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