SYMPOSIUM GI02

Materials for Next-Generation Robotics
November 26 - November 28, 2018

Symposium Organizers
Donglei (Emma) Fan, University of Texas at Austin
Peer Fischer, Max Planck Institute for Intelligent Systems
Rebecca Kramer-Bottiglio, Yale University
Bradley Nelson, ETH Zürich

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* Invited Paper

SESSION GI02.01: Actuators
Session Chair: Peer Fischer
Monday Morning, November 26, 2018
Hynes, Level 1, Room 111

8:30 AM *GI02.01.01
Unleashing your Inner Maker Daniela Rus; EECS, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

The digitization of practically everything coupled with the mobile Internet, the automation of knowledge work, and advanced robotics promises a future with democratized use of machines and wide-spread use of robots and customization. While the last 60 years have defined the field of industrial robots, and empowered hard bodied robots to execute complex assembly tasks in constrained industrial settings, the next 60 years will be ushering in our time with Pervasive robots that come in a diversity of forms and materials, helping people with physical tasks. However, pervasive use of robots remains a hard problem. How can we accelerate the creation of robots customized to specific tasks? Where are the gaps that we need to address in order to advance toward a future where robots are common in the world and they help reliably with physical tasks? In this talk I will discuss recent developments toward pervasive robots the role of computation in (1) on demand creation of robots, (2) making robots more capable of reasoning in the world, and (3) making more intuitive interfaces between robots and people.

9:00 AM *GI02.01.02
Artificial Muscle Fibers and Soft Sensors for Robotics—Some Example Materials, Opportunities and Challenges John D. Madden, Mirza S. Sarwar, Yuta Dobashi and Claire Preston; Univ of British Columbia, Vancouver, British Columbia, Canada.

Developments in materials promise to help improve the skin and muscle of robots and prothetics - in both hard and soft machines. Here the potential of supercoiled polymer fibres is explored as a 'muscle'. Elastomer and gel-based sensors are proposed as the 'skin' that can actively or passively detect pressure, stretch, bend, proximity and - possibly - shear.

Coiled nylon and polyethylene actuators make use of anisotropies in thermal expansion coefficents in order to generate strains that are similar to or larger than those of muscle. They can operate under much larger loading conditions. Low cost and ready availability makes these interesting for robotics. Challenges are speed, efficiency and shape memory effects. In comaparing requirements of various robotic actuators with the specifications of this artificial muscle, some application areas are identified, along with a path for further materials and device development.

In order for robots and prosthetic limbs to be dexterous, sensation is essential. Thin sheets of eastomers can be combined with gels and other conducting mateirals to simultaneously sense multiple inputs. One approach uses capactive sensing, similar to that on a touch screen - but in a stretchable format. Some challenges include distinguishing between the touch of a finger, the stretch or bend of the sensor, and forces - normal or shear. Early work shows an ability to discriminate between these modes, while detecting finger proximity within about 1 cm, and very light touch. Another sensor type, which is loosely dubbed piezoionic, makes use of the voltages and currents generated by differences in ion mobilities produced by the deformation of ionically conductive materials. These can be slow, but sensitivity is similar to piezoelectrics. Fast response is obtained by ionic double layer sensors, where changes in contact area between gels and metals lead to 0.5 V amplitude responses with no input electrical energy. Combining these two modes of sensing could provide a mix of fast and slow 'receptors' that require no electrical power input to run.

Looking ahead, how do we integrate actuators and sensors into complex robots - or even make the electrical & mechanical connections between soft and hard materials? And will we need to replace or regenerate materials? Muscle can undergo billions of cylces- while artificial muscle reaches 1/10th that at its very best. Successful approaches will need to combine materials, processing, design, manufacturing and cycle life considerations.

9:30 AM *GI02.01.03
Reprogrammable Shape-Memory Polymer Actuators for Robotics Andreas Lendlein[1, 2]; [1]Institute of Biomaterial Science, Helmholtz-Zentrum Geesthacht GmbH, Teltow, Germany; [2]Institute of Chemistry, University of Potsdam, Potsdam, Germany.

The classical shape-memory effect in polymers has so far been limited to its one way character, one time shape change. This limitation was overcome with the realization of shape-memory polymer actuators, which can repetitively change their shape under stress-free conditions [1]. A conceptual novelty in this

soft actuator class is the re-programmability of the shape changing geometry and the switching temperature. The reversible actuation can occur many times upon heating and cooling within a suitable temperature interval. Besides the geometry of movement, the switching temperature could be made programmable in temperature-memory polymer actuators [2]. Interestingly, semi-interpenetrating polymer networks, obtained by incomplete crosslinking, additionally exhibited a pronounced self-healing capability [3].
With the availability of such shape-memory polymer actuators (SMPA) being able to bend, twist or contract fully reversibly upon cyclic temperature changes, the next generation of reprogrammable, adapting robots seems to be approachable [4]. A prospect, of what can be achieved, is given by a demonstration of a twisted, non-continuously responding SMPA, which reversibly turns an arrow sign between three different positions in the hand of a manikin [5].

[1] M. Behl, K. Kratz, U. Nöchel, T. Sauter, A. Lendlein, Proc. Natl. Acad. Sci. U. S. A. 110, 12555−12559 (2013).
[2] M. Behl, K. Kratz, J. Zotzmann, U. Nöchel, A. Lendlein, Adv. Mater. 25, 4466-4469 (2013).
[3] M. Farhan, T. Rudolph, U. Nöchel, K. Kratz, A. Lendlein, Polymers 10, 255 (2018).
[4] A. Lendlein, Science Robotics 3, eaat9090 (2018).
[5] M. Farhan, T. Rudolph, U. Nöchel, W. Yan, K. Kratz, A. Lendlein, ACS Appl. Mater. Interfaces 9, 33559−33564 (2017).

10:00 AM BREAK

10:30 AM *GI02.01.04
HASEL Artificial Muscles—Versatile High-Performance Actuators for Next-Generation Robotics Christoph Keplinger; University of Colorado-Boulder, Boulder, Colorado, United States.

Actuators are key components of robotic systems. Robots today predominantly rely on rigid components and electric motors based on metal and magnets. The limited choice of materials and actuators restrains the capabilities of robots, which are heavy, complicated, expensive, often unsafe near humans, and ill-suited for unpredictable environments. Nature, in contrast, makes extensive use of soft materials and has produced living systems that drastically outperform robots in terms of agility, dexterity, and adaptability. Biological muscle is a masterpiece of evolution, featuring astonishing all-around actuation performance, the ability to self-heal after damage, and seamless integration with sensing in a soft matter based system. Advances in materials science and actuation mechanism are necessary to overcome limitations of traditional robotic hardware and enable a new generation of bio-inspired robots which replicate the vast capabilities of biological systems.

This talk gives an overview of a new class of self-sensing, high-performance artificial muscles, termed Hydraulically Amplified Self-healing ELectrostatic (HASEL) transducers. HASEL actuators are electrically driven and harness a mechanism that couples electrostatic and hydraulic forces to achieve a wide variety of actuation modes. Several different designs and fabrication strategies, as well as prototypical applications are introduced. Using only off-the-shelf materials, current designs of HASEL are capable of exceeding actuation stress of 0.3 MPa, linear strain of 100%, specific power of 800W/kg, full-cycle electromechanical efficiency of 30% and bandwidth of 50Hz. All these metrics match or exceed the performance of biological muscle. Additionally, HASEL actuators can repeatedly and autonomously self-heal after electric breakdown, thereby enabling lifetimes of a few million cycles at muscle-like levels of strain. Further, this talk introduces a facile fabrication technique that uses an inexpensive CNC heat sealing device to rapidly prototype HASELs. New designs of HASEL incorporate mechanisms to greatly reduce operating voltages, enabling the use of lightweight and portable electronics packages to drive untethered soft robotic devices powered by HASELs. Finally, a model of linearly contracting Peano-HASEL actuators predicts the behavior and scaling laws of these actuators, laying out a roadmap towards future HASEL actuators with drastically improved performance. These results highlight opportunities for the materials science community to further develop HASEL artificial muscles for wide use in next-generation robotic devices.

11:00 AM GI02.01.05
Rapid Prototyping of HASEL Actuators for Versatile and High-Speed Artificial Muscles Shane K. Mitchell[1], Xingrui Wang[1, 2], Eric Acome[1], Trent Martin[3], Khoi Ly[1], Nicholas A. Kellaris[1, 4] and Christoph Keplinger[1, 4]; [1]Mechanical Engineering, University of Colorado Boulder, Boulder, Colorado, United States; [2]Tongji University, Shanghai, China; [3]Electrical, Computer & Energy Engineering, University of Colorado Boulder, Boulder, Colorado, United States; [4]Materials Science and Engineering, University of Colorado Boulder, Boulder, Colorado, United States.

Soft robots with outstanding agility and dexterity require versatile and high-speed artificial muscles. Recently developed hydraulically amplified self-healing electrostatic (HASEL) actuators open new opportunities to create high-performance muscle mimetic actuators that are electrically driven, energy efficient, and capable of self-sensing their deformation. Initial prototypes of HASELs utilized fabrication techniques not easily modified to iterate designs and required bulky high voltage driving electronics. Here, we describe a facile fabrication technique that uses an inexpensive CNC heat sealing device to rapidly prototype complex designs of HASEL actuators using only off-the-shelf materials. We fabricate HASELs which feature linear and out-of-plane deformations and harness electrostatic zipping mechanisms to reduce operating voltages, thereby allowing us to demonstrate a lightweight and portable electronics package for untethered operation of these soft robotic devices. We show designs of HASEL which features linear strains up to 118 %, strain rates of 13,000 %/s, and power densities greater than 800 W/kg. These metrics enable actuators that are fast and powerful enough to jump, while rapid design iteration allows us to create continuum actuators with three-dimensional mobility. We further prototype designs for HASEL actuators to create bio-inspired curling actuators which mimic the high-speed strike of a scorpion tail. We show that these curling actuators can also operate as multifunctional grippers and shape-morphing structures. This presentation will highlight opportunities to further develop HASEL actuators tailored towards a variety of applications in robotics

11:15 AM GI02.01.06
Dielectric Elastomer Actuators as Soft, Energy Dense, Artificial Muscles Mihai Duduta, Ehsan Hajiesmaili, Huichan Zhao, Robert Wood and David Clarke; Harvard University, Cambridge, Massachusetts, United States.

Soft robotics represents a new set of technologies aimed at operating in natural environments, including near, or inside the human body. To move within and interact with their environment, soft robots require artificial muscles to actuate movement. These artificial muscles need to be as strong, fast, and robust as their natural counterparts. Dielectric elastomer actuators (DEAs) constitute a highly promising class of materials, but typically exhibit low output forces and low energy densities, when used without rigid supports. Here we report a soft composite material made of strain stiffening elastomers and carbon nanotube electrodes, which actuates under an applied electric field and demonstrates a peak energy density of 19.8 J/kg. The result is close to the upper limit for natural muscle (40 J/kg) making these DEAs the highest performance electrical driven artificial muscles. To obtain high forces and displacements, we used low density, ultra-thin carbon nanotube electrodes which can sustain applied electric fields upwards of 100 V/micron, without suffering from dielectric breakdown. The fabrication process described herein is fast, scalable, and uses relatively low cost components and equipment. Potential future applications include biomedical uses, such as prosthetics, surgical robots, and wearable devices, as well as more capable soft robots capable of locomotion and manipulation in natural or human-centric environments.

11:30 AM GI02.01.07

Hybrid Soft Dielectric Elastomer Robots Exploiting Pneumatics to Generate Large Actuation Ernst-Friedrich M. Henke[1, 2, 3], Sascha Pfeil[1, 3] and Andreas Richter[3]; [1]Solid State Electronics Lab, TU Dresden, Dresden, Germany; [2]Auckland Bioengineering Institute, The University of Auckland, Auckland, New Zealand; [3]Institute of Semiconductors and Microsystems, TU Dresden, Dresden, Germany.

Multifunctional Dielectric Elastomer (DE) devices are well established as actuators, sensors and energy harvesters. Since the invention of the DE Switch (DES), a piezoresistive electrode that can directly switch charge on and off, it became possible to expand the wide functionality of dielectric elastomer structures even more.
It is possible to couple arrays of actuator/switch units so that they switch charge between themselves on and off. One can then build DE devices that operate as self-controlled oscillators. With an oscillator one can produce a periodic signal that controls a soft DE robot. Now one has a DE device with its own DE nervous system.
We have demonstrated a variety of components for autonomous soft robots without conventional electronics. The combination of digital logic structures for basic signal processing, data storage in dielectric elastomer flip-flops and digital and analogue clocks with adjustable frequencies, made of dielectric elastomer oscillators (DEOs), puts us in the position to design self-controlled and electronics-free robotic structures.
The last remaining stiff structures in DE robotic structures were stiff PMMA frames to maintain necessary pre-strains to enable sufficient actuation of dielectric elastomer actuators (DEAs). Here we present a design and production technology for a first robotic structure consisting only of soft silicones and carbon black. We present different promising designs for entirely soft DE-driven robots.
We present the design of the hybrid, soft DE robots exploiting pneumatics for pre-stretching their muscles. It combines the advantages of pneumatic pre-stretching DE membranes with the electronic control of DE muscles. This approach reduces the complexity of the necessary pneumatic control units driving the robot, it only needs a constant internal pressure. We present a circular crawling robot that is designed in such a way that an internal pneumatic pressure only leads to an elongation in longitudinal direction, but not in radial direction. This design prevents an inflation of the DE muscles, and, thus keeps the diameter of the structure constant. The actuation is generated by pulsing electric signals applied to the robot's muscles. The elongation of the individual muscle segments is then transformed into an actuation by directional friction structures. We present the design of the robot an analytical and a FEA model and the first experimental results.

11:45 AM GI02.01.08

Brilliantly Structured Light-Weight Twisted-Coiled Fiber Actuators Using Polymer Threads and Twisted Dry Spun Carbon Nanotube Yarns Bringing Out High Actuation Performance Yasuhiko Hayashi[1, 2], Takayuki Yoshiyama[1], Hirotaka Inoue[1], Masaki Hada[1, 2], Daiki Chujo[1], Yoshitaka Saito[3], Karthik Paneer Selvam[1], Wataru Takarada[3] and Hidetoshi Matsumoto[3]; [1]Graduate School of Natural Science and Technology, Okayama University, Okayama, Japan; [2]Institute of Innovative Research, Tokyo Institute of Technology, Tokyo, Japan; [3]Department of Materials Science and Engineering, Tokyo Institute of Technology, Tokyo, Japan.

Fiber actuators have attracted considerable attention as they are not only lightweight but also can generate a large strain, they realize human mimetic motions that are strongly demanded in the field of soft robotics. One of the crucial challenges presented by self-contained electrically heat driven coil-shaped fiber actuators resides in their thermal absorption and contraction twitch. So far, coil-shaped polymer actuators wrapped with copper wire or silver paste as heating sources were reported. However, the use of metals increases the weight of the fiber actuators and effect their flexibility. Also, the difference in the thermal expansion coefficients between the polymer thread and accompanying metal frame may degrade the performance of actuation motions.

Hear, three types of coil-shaped polymer fiber actuators were fabricated from poly(ethylene terephthalate) (PET) threads as actuators and high thermal conducting twisted dry spun carbon nanotube (CNT) yarns as heating wires. We analyzed the thermal absorb desorb effects on their performance concerning their mechanical force.

The diameter of a PET fiber was approximately 20 μm. The lengths of PET threads and CNT yarns were 15 cm. The "MultiF-A" is composed of the PET threads and CNT yarns homogeneously. These fibers contain randomly in their cross section profile and they were rotated until it changes to coil-shaped structure. The "MultiF-B" is composed of few fine coil-shaped threads. At first, two CNT yarns and four PET threads are bundled and rotated. And then, a certain number of fine coil-shaped PET/CNT fibers are bundled. The "MonoF" is fabricated from a bundle of PET threads and a bundle of CNT yarns, similar to the reported fiber actuator made from one polymer fiber and one heating wire.

The applied electric power to CNT yarns was maintained constant at 50 mW (5 mW per CNT yarn). The mechanical force linearly increases as the number of PET threads are increased in all types of fiber actuators. The mechanical force generated in MultiF-A and -B is 1.6 times higher than that generated in the MonoF. The responsivities (heating and cooling processes) of the fiber actuator strongly depends on the time constant of the deformation of PET threads, and therefore the response behaviors of the three types of fiber actuators are identical. The amount of displacement of MultiF-A and -B is 1.4–1.8 times higher than the MonoF at 50 mW. This is in good agreement with the result obtained by the measurements of mechanical force.

A more in-depth analysis of the thermal effects on the fiber actuator was performed by constructing a model including both MultiF-A and MonoF. The MultiF-A is homogeneously thermalized with the input energy, however, the MonoF shows inhomogeneous thermal distribution.

Based on our results, homogenous thermal distribution in the fiber actuators realized by brilliant structure is key factor for the highest actuation performance.

SESSION GI02.02: Responsive Materials
Session Chair: Peer Fischer
Monday Afternoon, November 26, 2018
Hynes, Level 1, Room 111

1:30 PM *GI02.02.01

Materials for Next Generation Robotics Soft Materials and Soft Robotics for Future Robot Abilities and Applications Cecilia Laschi and Matteo Cianchetti; The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Pisa, Italy.

Though a young discipline, robotics progressed rapidly and pervaded our lives more than we perceive, becoming a tool we cannot do without in

manufacturing. Futuristic scenarios have been proposing robots in daily life of citizens and professionals for decades, creating expectations that have not yet been matched. What is the real status of development of robotics today and what are the realistic scenarios that robotics technologies enable today? What are the abilities that robots still miss to match expectations for extensive application and healthier and safer human life?
Largely inspired by the observation of the role of soft tissues in living organisms, the use of soft matter for building robots is recognized as one of the current challenges for pushing the boundaries of robotics technologies and building robotic systems for service tasks in natural environments. The study of living organisms sheds light on principles that can be fruitfully adopted to develop additional robot abilities or to facilitate more efficient accomplishment of tasks, because living organisms exploit soft tissues and compliant structures to move effectively in complex natural environments. The compliance and the elasticity of soft body parts, and especially a tunable stiffness, allow purposive reactions to interaction forces. So-called Soft Robotics is the use of soft materials or deformable structures in robotics. The wide spreading of soft robotics research worldwide has brought significant achievements in terms of principles, models, technologies and prototypes.
The main characteristic of compliance makes softs robotics technologies particularly well suited for biomedical applications, where robots have to interact effectively and safely with a patient. Soft robots are well suited when used in direct contact with a patient, like in surgery in rehabilitation and assistance. A soft manipulator can move safely inside the human body and act as an endoscope or change its stiffness to perform surgical procedures. A soft arm can help elderly people in bathing activities by becoming a robotic shower, able to approach and interact safely yet effectively with the user. In addition to this, soft robotics technologies are useful for building simulators of body parts, for medical studies and training, like the vocal cords or the minute lungs of pre-term babies. Explorations are also a terrific field of applications for soft robots, that can reach remote inaccessible areas, including and especially underwater. Advances in soft materials, smart materials and energy harvesting represent today the main line of robotics progress.

2:00 PM GI02.02.02
Multi-Responsive Tactile Hydrogels as Soft Robotic Materials Ximin He, Yixuan Xu, Yusen Zhao and Mo Sun; University of California, Los Angeles, Los Angeles, California, United States.

Stimuli-response hydrogels have found tremendous applications as adaptive lenses, artificial muscles, vehicles for drug deliveries, scaffolds or matrices for tissue engineering, as well as sensors and actuators for soft robotics and soft machines. Here we report a tough, conductive, multi-responsive hydrogel, which is designed and synthesized by one-step polymerization with double network made of conductive polymer and chemically nano-crosslinked hydrogels. This hydrogel possesses a highly mechano-electrically sensitive that can change shape rapidly at large ratios upon local sensing of the approaching of an arbitrary object in contact with the hydrogel. This smart hydrogel can change its volume in response to subtle mechanical force and electric signals like the neural commands and acute tactility of octopus or human skin when it is in contact with an object. This presents a novel capability of force-induced shape changing, achieved through the force-electro-mechanical energy transduction within the gel materials. Overall, the important novel characteristic of this force-sensitive tactile hydrogel is the capability of detecting the geometry or rigidity of the environment and adaptively changing its own shape to adapt to the shape of the environment. For example, such gel can behave as a fully automatic gripper without external control, which can grasp an object in arbitrary shape that is poking the gel. Additionally, this hydrogel is highly strong mechanically. Unlike previously developed pneumatic or hydraulic soft robotic arms and manipulators, our tactile hydrogel-based robotic materials will be self-contained and capable of continuous “sense-diagnose-response” to perform adaptive configuration changes without incurring damage.

2:15 PM GI02.02.03
Fabric Reinforced Hydrogel/Elastomer Composites for Stimuli-Responsive Actuators Daniel R. King[1, 2], Amber M. Hubbard[3], Wei Cui[4], Yiwan Huang[1], Michael Dickey[3], Jan Genzer[3, 2] and Jian Ping Gong[1, 2]; [1]Faculty of Advanced Life Science, Hokkaido University, Sapporo, Japan; [2]Global Station for Soft Matter Research, Sapporo, Japan; [3]Chemical and Biomolecular Engineering, North Carolina State University, Raleigh, North Carolina, United States; [4]Graduate School of Life Science, Hokkaido University, Sapporo, Japan.

Hydrogels are useful in biomaterials applications, but often lack the robust mechanical properties seen in nature. Natural materials rarely consist of discrete independent materials, rather utilizing composite structures to achieve significant mechanical properties. Here, we report the use of fabrics as a reinforcing phase within hydrogel matrices. The use of fabric results in many preferential properties. During tearing, we observe a synergistic increase in fracture strength due to a dramatically enlarged process zone in the composite structure. Furthermore, the hydrogel composites possess high stiffness in plane, while maintaining flexibility. Building upon this idea, we have recently utilized glass fiber fabric as an interphase to create tri-layer laminates consisting of both hydrogel and elastomer. This technique allows us to strongly bind two very dissimilar materials together, while boosting the strength and toughness. Importantly, this method does not depend on chemistry, and can be applied generally. When exposed to preferential solvents, these tri-layer laminates can be utilized as actuators. Bending rotations up to 50 degrees have been achieved, and strain intensities of approximately 25% of human muscles have been recorded. These results demonstrate the usefulness of fabric as a component in soft composite materials, and provide a method to create active materials which will be useful in soft robotic applications.

2:30 PM GI02.02.04
A Soft Pneumatic Haptic Actuator Mechanically Programmed for Providing Tactile Perception Juan Huaroto[1], Victor Ticllacuri[1], Etsel Suarez[1], Robert Ccorahua[1] and Emir Vela[1, 2]; [1]Biomedical Engineering joint program PUCP-UPCH, Escuela Profesional de Ingenieria, Facultad de Ciencias y Filosofia, and Laboratorios de Investigacion y Desarrollo - LID, Universidad Peruana Cayetano Heredia, Lim, Peru; [2]Department of Electrical and Computer Engineering, The University of New Mexico, Alburquerque, New Mexico, United States.

In recent years, haptics has been used in different topics as biomedical devices, teleoperation, computer games, among others. Haptic biomedical devices mainly provide tactile feedback over skin to raise patients sensitivity. Most of these devices are stiff and comprise complex mechanisms. On the other hand, materials like rubber and silicones have showed remarkable properties: comfortability, safety, esthetics and reliability for this sort of devices, performing inherent compliance of soft materials. However, to date soft haptic devices are only used for the application of pressures and/or vibrations onto skin. In this context, herein a new soft pneumatic haptic device is proposed. This was based on arrays of different layers of rubber composite materials that allow complex movements over skin, such traction in two and combined directions. Soft haptic device were fabricated using two different types of silicone, taking into account his stiffness and compliance. First, we cure one compliant layer that contains two different types of silicone in complementary different shapes. In order to define the actuator chamber geometry, a sheet of fabric is cut with the desired shape and then is stuck in its edges over the aforementioned layer using silicone adhesive (Sil-Poxy, Smooth-On). Then we cure a second layer of silicone using the stiffer silicone in order to seal the actuator. It is observed that the planar shape defined by the sheet of fabric geometry influences the actuator inflation profile, on the other hand the complementary different shapes and material stiffness allows that the inflation process be non-uniform in all of the actuator surface. These two different advantages in the fabrication process, allow us to program different shapes of fabric, planar geometries of silicone and stiffness. This also permit developing an actuator with a defined and complex shape of inflation that can be perform a relative displacement of 14 mm at 50 kPa between two zones of the actuator membrane. Static simulations were performed in the software ANSYS (static structural package), taking into account uniaxial test data from a hyperelastic materials such as: Dragon skin 30 (Smooth-On), Ecoflex 0030 (Smooth-On) and RTV 1520. By means of this simulation process, the planar geometries of actuator chamber and the complementary geometries for each type of silicone were changed, obtaining the optimized design for the desire

application. At the end, the results are compared with manufactured prototypes for standard forearm dimensions contrasting our results using characterization approaches. These preliminary results were suggest the potential of employing this haptic device, besides his softness, compliance, low cost and safety over skin, provide different tactile perceptions for upper limb amputees based on Extended Physiologic Taction (EPT).

2:45 PM GI02.02.05
Opto-Mechanical Azo Dye Polymers—New Light on Mechanism and Optimization for Soft Material Robotics Christopher Barrett[1, 2] and Atsushi Shishido[2]; [1]McGill University, Montreal, Quebec, Canada; [2]Tokyo Institute of Technology, Tokyo, Japan.

Polymer materials incorporating azobenzene dye can function as mimics of the retinal photo-switch that enables vision, responding physically and mechanically to permit visible light to be converted directly to mechanical work. Reversible changes in surface energy are also inducible as a result, for a variety of reversible surface energy switching applications via light. Irradiation with light in the solar spectrum at sun-like intensities will be shown to lead to a measurable reversible photo-expansion of these coatings, of up to a few %, allowing the materials to function as photo-mechanical switches or light energy harvesters and actuator devices. New azo liquid crystal materials and polymers to optimize this effect will be presented, and some simple macroscopic devices will be demonstrated that take mechanical advantage of this effect for larger scale motion driven by sunlight.

The mechanism for this effect will be discussed from studies using ellipsometry, light-bending of AFM cantilevers, high-pressure raman spectroscopy, and neutron reflectometry. In particular, recent materials preapred from pseudostilbene-type azo molecules exhibit unusually fast, and reversible photomechanical motion under visible-light irradiation, with the extremely rapid switching using just one wavelength of light by shortening the lifetime of the *cis*-form. This results in a bending motion in the microsecond regime. The influence of density, thickness, and molecular orientation on optimization of the photomechanical effect will be discussed. Lastly, some simple soft-robotic proof-of-principle devices will be presented, that upon visible irradiation, can bend and wiggle; crawl, walk, and roll.

3:00 PM BREAK

SESSION GI02.03: Robots
Session Chair: Rebecca Kramer-Bottiglio
Monday Afternoon, November 26, 2018
Hynes, Level 1, Room 111

3:30 PM *GI02.03.01
Bio-Inspired Tactile Sensing Skins for Robots Elisabeth Smela, Ying Chen, Miao Yu and Hugh Bruck; Department of Mechanical Engineering, University of Maryland, College Park, Maryland, United States.

Robots working in unstructured situations, particularly around humans, need to detect the occurrence and location of physical contacts with objects or people, not only for safety but also to enable touch-based communication. Care-giving and factory floor environments are two examples. It is also advantageous in these scenarios if the robot is padded. This led to our exploration of stretchable tactile sensing skins, which can accommodate the large deformations experienced during contact and which can be produced at whole-body scales. In fact, the response of piezoresistive strain sensors is amplified by localized deformation in the foam. The advantages of soft materials are, however, tempered by their concomitant time and history-dependent mechanical responses. The behavior of the foam, in particular, can dominate the response from the sensor. The readings from the skin may be useful nonetheless because a robot may only need to determine the nature, magnitude, and location of contacts rather than exact force values for operational success. The use of multilayered or geometrically restricted architectures can aid the interpretation of data obtained during contact, as can the use of techniques such as electrical impedance tomography (EIT) for distributed sensing, particularly for interpreting human touches such as multi-point finger presses and sliding. For example, while information from a single sensing layer on foam can reasonably distinguish forces applied by a machine, two stretchable sensing skins alternating with two foam layers are superior for interpreting highly variable human touch. Use of multiple layers also permits higher sensitivity readings at low force coupled with an extended high force range. To move forward in this effort, it is critical to address integration issues, particularly the formation of good electromechanical connections between the soft materials and the rest of the platform. Another challenge is improving the stability and robustness of the soft sensors.

4:00 PM GI02.03.02
Towards Damage Resilient Soft-Matter Robotics and Electronics Eric Markvicka[1], Michael D. Bartlett[2], Xiaonan Huang[1], Ravi Tutika[2] and Carmel Majidi[1]; [1]Carnegie Mellon University, Pittsburgh, Pennsylvania, United States; [2]Iowa State University of Science and Technology, Ames, Iowa, United States.

Emerging applications in soft robotics, human-machine interaction, and wearable robotics will increasing rely on new soft-matter technologies that are considered inherently safe as they are primarily composed of intrinsically soft materials—elastomers, gels, and fluids. These materials provide a method for creating soft-matter counterparts to traditionally rigid devices that exhibit the mechanical compliance of natural, biological systems. However, these soft-mimics are increasingly susceptible (as compared to their rigid counterparts) to varying forms of mechanical damage such as cutting, tearing, or puncture that can result in operational failure. Here, a new material architecture will be presented for creating soft and highly deformable circuit interconnects. The traces are electromechanically stable under typical loading conditions, and exhibit uncompromising resilience to mechanical damage—cutting, tearing, or puncture. The material is composed of micron-scale droplets suspended in a soft elastomer; when damaged, the droplets rupture to form new connections with neighbors and re-route electrical signals without interruption. Since self-healing occurs spontaneously, these materials do not require manual repair or external heat. We demonstrate this unprecedented electrical robustness using a self-healing soft robotic quadruped that continues to function after significant damage. We will also present a recently developed method for actively sensing and localizing damage (compression, cutting, and puncture) within a thin elastomer film. When coupled with processing, actuation, and communication, this soft and highly deformable composite presents new opportunities to identify and respond to mechanical damage in soft-matter robotic systems.

4:15 PM GI02.03.03
Biodegradable Soft Robots with Electronic Skins Florian Hartmann, Melanie Baumgartner, Michael Drack, David Preninger, Stepan Demchyshyn, Robert Gerstmayr, Daniela Wirthl, Lukas Lehner, Siegfried Bauer and Martin Kaltenbrunner; Johannes Kepler University, Linz, Austria.

Cephalopods, caterpillars and other soft creatures inspired a broad spectrum of bio-mimetic actuators -- enhanced with perceptive electronic skins --

capable of sensing and adapting to their complex erratic environments. Yet, they are missing a feature of nature's designs: biodegradability. Soft robots that degrade at the end of their life cycle reduce electronic waste and are paramount for a sustainable future. At the same time, medical (robotic) technologies have to address hygiene requirements. We therefore develop biodegradable hydrogels for single-use wearable electronics and transient soft robots that are reversibly stretchable, are able to heal and are resistant to dehydration. Soft machines and robots -- built from hydrogels with tuned mechanical properties -- are designed to be operated in ambient conditions and degrade after use. An equally compostable electronic skin provides our soft actuators tactile feedback and temperature sensing, directly processed with a recyclable on-board computation unit. Besides progressing stand-alone soft machines, our advances in the synthesis of biodegradable hydrogels bring bionic soft robots a step closer to nature.

4:30 PM GI02.03.04

Electronic Epidermis That Activates Soft Robots Wirelessly Junghwan Byun[1, 2], Yoontaek Lee[1, 3], Jaeyoung Yoon[1, 3], Yongtaek Hong[1, 3] and Kyu-Jin Cho[1, 2]; [1]Seoul National University, Seoul, Korea (the Republic of); [2]Soft Robotics Research Center, Seoul, Korea (the Republic of); [3]Inter-university Semiconductor Research Center, Seoul, Korea (the Republic of).

A recent stream of research on robotics, called "Soft Robotics", aims for designing softness into each robot part on the basis of soft materials and body architectures. Reducing rigid boundaries of robots greatly improves robotic compliance to dynamic, unstructured environments in terms of adaptiveness. In this regard, several studies have reported fabrication and integration methodologies for soft body architectures in which soft actuators or actuating frames are integrated into a soft body frame. Despite the body's softness, however, existing models mostly carry inherent hardness and bulkiness in their driving parts, such as pressure-regulating components and rigid circuit boards. This compliance gap can frequently interfere with the robot motion and makes soft robotic design dependent on rigid assembly of each robot component.
In this work, we report a class of electronic systems that can be softly and reversibly integrated as a "robotic epidermis" into soft robot frames and then can activate (and control) them wirelessly. The proposed electronic epidermis (e-epidermis) is soft (~30% stretchable), thin (<1 mm), lightweight (<1 g), and involves driving capability on the basis of controlled Joule heating. The electronic functionality with skin-like mechanical property is designed by stretchable hybrid electronics (SHE) layouts. A large number of surface mountable devices (SMDs) are directly assembled onto a soft substrate and bridged by inkjet-printed stretchable interconnection networks (silver thin films with wrinkled geometry) to achieve adequate circuit architectures for wireless robot control. In particular, the size of the assembled SMDs is regulated ($\leq 1.5 \times 1.5 \times 0.6$ mm^3) for the e-epidermis to share the large local bending curvature which can be the deformation profile of soft robots. The resulting e-epidermis can not only mechanically conform to dynamic surfaces like soft robot frames but also activate soft actuators through controlled current driving. Benefits of this design enable compact integration of fully soft robots. We demonstrate a thin (total thickness< 2 mm), compact, soft robotic hand whose body dimension in itself cannot possibly equip any other types of conventional driving systems. This fully soft robot can be actuated and mechanically deformed in ways not previously possible: a body architecture and embedded e-epidermis can equally share the sequential deformation profiles. Furthermore, this e-epidermis concept provides universality for robotic actuation based on reversible assembly.
This work was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korean Government (MSIP) (No. NRF-2016R1A5A1938472).

4:45 PM GI02.03.05

Self-Healable Stretchable Light Sources Benjamin C. Tee[1, 2, 3], Yu Jun Tan[2] and Hareesh Godaba[1]; [1]Materials Science and Engineering, National University of Singapore, Singapore, Singapore; [2]Biomedical Institute for Global Health Research and Technology, National University of Singapore, Singapore, Singapore; [3]Institute of Materials Research and Engineering (IMRE), Agency for Science Technology and Research, Singapore, Singapore.

Most human-machine interfaces rely on some form of visible light sources such as light emitting displays. In flexible and stretchable electronics, exciting progress has been made via the use of strain robust electronic devices for advanced soft robotics[1], wearable biomedical devices[2] and flexible touch interfaces[3]. On the other hand, self-healing and self-repairable materials and devices are gaining tremendous interest due to the possibility of reducing technological waste[4–6]. Hence, it is useful to investigate stretchable light sources that could have self-repair functions for such applications. In this talk, I will describe a stretchable and self-healable electroluminescent (EL) material that can stretch elastically. The material processing is facile, and the devices can withstand multiple mechanically inflicted 'wounds' and recover functionality. Such materials can be integrated into devices for emerging wearable soft robotics and human-machine interactions.

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SESSION GI02.04: Structures
Session Chair: Donglei (Emma) Fan
Tuesday Morning, November 27, 2018
Hynes, Level 1, Room 111

8:00 AM *GI02.04.01

Navigable Soft Robotic Microcatheter for Endovascular Treatment of Cerebral Aneurysms James Friend; University of California, San Diego, La Jolla, California, United States.

We report a unique solution of an unmet clinical need in vascular microsurgery using a combination of novel 10-100-µm scale soft polymer cast-and-print fabrication techniques, simple microhydraulics, hyperelastic media with tailored nonlinear elasticity properties, and carefully designed, complex cross-sectioned microstructures. The third most common cause of death in the United States, strokes present a tremendous sociological and economic burden.

While rapid, minimally invasive surgical intervention is sometimes beneficial, the crude tools available today are completely inadequate. We focus upon the most serious problem in stroke intervention: intracranial aneurysms. Nearly one-fourth of neurointerventions fail due to the difficulty in navigating the microcatheter to the aneurysm location through tortuous vasculature and in orienting the microcatheter tip in the aneurysm dome to an optimal position for coil deployment to close off the aneurysm.

Our approach produces a completely steerable microcatheter at the small (~100 µm) scales necessary for endovascular neurosurgery via direct hydraulic microactuation and a hand controller simple enough for a neurointerventionist to use. With data from ex-vivo and in-vivo animal trials, we show the technology quantifiably produces better outcomes, fewer mistakes, speeds treatment, and enables greater treatment capabilities than current state-of-the-art devices. Our ex-vivo testing furthermore employs new MRI-to-in-silico models printed from anonymized angiograms of patients with aneurysms. The models include accurate blood flow and neurovascular elasticity, and such minor but important details as the surgical bed and the extended vasculature from the groin through the aorta, heart and chest to the neurovasculature. Beyond the neurovasculature and steering, ideas on the next generation of facile, distal microactuation for biopsy, suturing, drug delivery, and many other applications via our technology will be proffered to result in improved patient outcomes and reduced healthcare costs for all.

8:30 AM *GI02.04.02

Photoalignment Control and Mechanical Analysis of Polymer Films for Soft Robotics Atsushi Shishido; Tokyo Institute of Technology, Yokohama, Japan.

Macroscopic alignment control of liquid crystal (LC) films is key to the development of next-generation high-performance soft robot materials. Current methods achieve such large-area alignment of LCs, having intrinsic structural ordering over various length scales from nanometer to micrometer, by applying uniform external fields along one direction, such as mechanical stress, surface rubbing treatment, and electromagnetic or light fields. Among these more advanced 2D techniques, light-driven alignment control (photoalignment) might provide the greatest potential for fine control over molecular orientation, because of its remote and precise influence, and suitability for micro- or nanofabrication, which can enable many applications that require more complex alignment patterns. With conventional photoalignment methods, one typically irradiates an LC film containing added photoresponsive molecules with spatiotemporally uniform polarized light. We report here a new concept of scanning wave photopolymerization (SWaP) using spatiotemporal scanning of UV light to start photopolymerization and create a mass flow in the film, which results in LC alignment coincident with the incident UV light patterns. Furthermore, we introduce mechanical analysis of such flexible polymer films to quantitatively understand a new mechanics for soft robotics.

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9:00 AM *GI02.04.03

Self-Growing Adaptable Soft Robots Barbara Mazzolai, Ali Sadeghi, Emanuela Del Dottore and Alessio Mondini; Istituto Italiano di Tecnologia, Pontedera, Italy.

Growth is a very interesting feature of living beings that can inspire a generation of robots endowed with new and unprecedented abilities of movement. Growth involves the cellular activity of both animals and plants, yet the evolution of organisms in these two kingdoms is completely different. Animals grow until maturity, while plants grow indefinitely, mostly for their entire life. Animal growth is also known as "determinate" growth, since trajectory and asymptotic size are usually genetically defined and environmental influence has a limited impact. Plant growth, on the other hand, is "indeterminate", since it extends throughout life. Growth allows a strong adaptation of body morphology to environmental conditions, also called plasticity, which characterizes the plant kingdom. Differently from animals, plants grow to move, in search for nutrients and light and for protection from harmful agents. Noteworthy, plants represent an alternative model of movement in robotics, which is not animal-like and muscle-based.
For the first time in robotics, we proposed a growing robot inspired by movements and behaviors of plant roots. The robot is able to create in real-time its own body structure exploiting a 3D printer-like system integrated in its tip for the deposition of a thermoplastic material, thus imitating the indeterminate axial growth and bending root abilities.
Passive and active movements in plants can also be exploited for developing multifunctional materials and energy-efficient actuators based on osmosis. Starting from the investigation of nutrient uptake phenomena, movements and communication strategies adopted by plant roots, we developed uptake–kinetics feedback control and self-organization ability for exploitation tasks.
Based on these plants' features, we can generate new, unexplored abilities in bioinspired robots, which can better adapt to external, unstructured environments, move purposively, effectively and efficiently.

9:30 AM GI02.04.04

Polymer Hydrogels for Artificial Transpiration in Biomimetic Plant Robots Doruk S. Cezan[1], Hasan T. Baytekin[2] and Bilge Baytekin[1, 2]; [1]Chemistry Department, Bilkent University, Ankara, Turkey; [2] National Nanotechnology Research Center (UNAM), Bilkent University, Ankara, Turkey.

Bio-inspired materials – using the strategies of nature to design materials – has many implications in fields extending from energy to medicine to robotics. In robotics, biological systems have been a great inspiration source owing to their fascinating abilities developed in the course of evolution. Plants, in particular, have interesting abilities like adaptability, sensing, self-regulation, self-healing, and unique surfaces structures that have great possibilities to feed ideas for new materials production. Especially interesting are heliotropism (solar tracking of plants), and nyctinasty (opening and closing leaves) in plants, used for achieving high-energy efficiency in photosynthesis. Previously, using shape memory alloys or liquid crystal structures, it was shown that plant robots, too, can possess these features but none of these robots were truly biomimetic. In this study, we demonstrate biomimetic robot plants, which display heliotropism and nyctinasty by artificial transpiration (water transport in plants) – the exact strategy used in nature. Several thermo-responsive hydrogels (PNIPAM, PDEAAM, and PNVCL) were used on a cellulose plant body to achieve the targeted biomimicry. The systems are assessed for the transpiration efficiency, actuation speed and its relevance to the sensory motion, as well as for their heliotropic efficiencies. The bioinspired approach used in this study for the plant robots and structures designed by using them could be of interest for autonomous soft robotic systems in which the motion solely controlled by materials.

9:45 AM GI02.04.05

Memory and Learning in Biomolecular Soft Matter for Low-Power Brain-Like Computing Joseph S. Najem[1, 2], Md Sakib Hasan[1], Ryan Weiss[1], Catherine Schuman[2], Alex Belianinov[2], Graham Taylor[1, 2], Garrett Rose[1], Stephen A. Sarles[1] and Charles P. Collier[2]; [1]The University of Tennessee, Knoxville, Knoxville, Tennessee, United States; [2]Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States.

The capacity of robots to learn, operate autonomously, and support other cognitive tasks independently in complex and dynamic environments will require approaches to computation that are inherently brain-like. Neuromorphic computing systems co-locate information processing and memory at levels approaching the density, complexity, and energy efficiency of the brain needed for the next generation of robotics.
Reproducing these features using traditional electronic circuit elements is virtually impossible, requiring the design and fabrication of new hardware elements that can adapt to incoming signals and remember processed information. We refer to these elements as mem-elements (short for memory elements), which are passive, two-terminal devices whose resistance, capacitance, or inductance remembers the past electrical activity of the device. These elements should be scalable, biomimetic, and preferably ionic to achieve energy consumption levels approaching those in the brain.
Here we describe two-terminal, biomolecular memcapacitors and memristors, consisting of highly insulating 5 nm-thick lipid bilayers assembled between two water droplets in oil. These devices exhibit memcapacitance that is nonlinearly dependent on the applied voltage, and hysteresis in the charge due to reversible changes in the area and thickness of the bilayer membrane in response to voltage. This is the first demonstration of a memcapacitor in which capacitive memory results from geometrical changes in a lipid bilayer membrane. We also show that the incorporation of voltage-activated alamethicin peptides in these devices results in variable ionic conductance across the membrane and memristive behavior.
We discuss how these devices exhibit learning through synaptic plasticity, and how to implement them in online learning applications. These results serve as a foundation for a new class of low-cost, low-power, soft mem-elements based on lipid interfaces and other biomolecules for applications in neuromorphic computing which could have major implications on the robotics field.

10:00 AM BREAK

SESSION GI02.05: Electronics, Memory and Perception
Session Chair: Peer Fischer
Tuesday Morning, November 27, 2018
Hynes, Level 1, Room 111

10:30 AM *GI02.05.01
The Mechanical Side of AI Robert Wood; Wyss Institute for Biologically Inspired Engineering and John A Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, United States.

Artificial Intelligence typically focuses on perception, learning, and control methods to enable autonomous robots to make and act on decisions in real environments. On the contrary, our research is focused on the design, mechanics, materials, and manufacturing of novel robot platforms that make the perception, control, or action easier or more robust for natural, unstructured, and often unpredictable environments. Key principles in this pursuit include bioinspired designs, smart materials for novel sensors and actuators, and the development of multi-scale, multi-material manufacturing methods. This talk will illustrate this philosophy by highlighting the creation of several classes of soft-bodied robots.

11:00 AM GI02.05.02
3D-Printable Shape-Morphing Architectures via Programmable Stress Duanduan Han and Victor Ugaz; Texas A&M University, College Station, Texas, United States.

Significant advancements in soft robotics have been achieved through the use of polymeric materials that actively respond to external stimuli via shape memory or physico-chemical interactions with their surroundings. And recent excitement has been generated by application of these responsive properties to produce shape-shifting 2D structures capable of morphing into complex 3D topologies. But manufacturing these active components generally requires specialized chemical formulations and sophisticated multi-material patterning capabilities that are not widely available outside research laboratory settings, significantly limiting their impact. Here we show how this barrier can be overcome by using 3D printing to embed prescribed internal stresses within a planar2D substrate. These stresses are controllably released in response to an external trigger, deforming the material into a desired 3D shape.

We apply this capability to construct active components relevant to soft robotics in three ways. First, we produce a library of building blocks embedding programmed internal stresses that can be assembled to enable 3D deformation with controllable local curvature. We then show how these elements can be combined to spatially distribute strain across multiple length scales, replicating hierarchical structures found in living systems. Finally, we apply these design principles to produce a self-assembled metal/air battery capable of functioning either as a stand-alone power source or as part of a self-powered electrochromic glucose sensor for use as a diagnostic tool in resource-limited settings. Notably, all of these components can be manufactured using standard 3D printers and materials, significantly broadening access to soft robotics technology.

11:15 AM GI02.05.03
Actively Perceiving and Responsive Soft Robots Enabled by Self-Powered, Highly Extensible, and Highly Sensitive Triboelectric Proximity- and Pressure-Sensing Skins Ying-Chih Lai[1] and Zhong Lin Wang[2]; [1]Materials Science and Engineering, National Chung Hsing University, Taichung City, Taiwan; [2]Georgia Institute of Technology, Atlanta, Georgia, United States.

We will propose the first demonstrations of using triboelectric effect to realize various actively sensing and responsive capabilities in soft robots. Robots that can move, feel, and respond like organisms will bring revolutionary impact to today's technologies. Soft robots with organism-like bodies have shown great potential in vast robot-human and robot-environment applications. Developing skin-like sensory devices allows them to naturally sense and interact with environment. It would be better if the capabilities to sense can be active like real skin. However, challenges in complicated structures, incompatible moduli, poor stretchability and sensitivity, large driving-voltage, and power dissipation hinder applicability of conventional technologies.
Here, for the first time, various actively perceivable and responsive soft robots are enabled by using self-powered active triboelectric robotic skins that simultaneously possess excellent stretchability and excellent sensitivity in low-pressure regime. The robots' skins can actively sense proximity, contact, and pressure to external stimuli via self-generating electricity. The driving-energy of its sensing ability comes from natural triboelectrification effect. Various kinds of perceiving soft robots will be demonstrated to use triboelectric effect to complete different actively sensing and responding tasks. For a conscious gripper, it can actively be aware of different actions in moving an object including approaching, grabbing, lifting, lowering, and even the accident of dropping off the objects. A perceivable robot-finger can check a baby's diaper condition. A conscious robotic crawler enable to perceive its muscle motions during undulating gaits and detect very subtle human physiological signals, showing their potential in palpation. Such robots with large-area skins have been demonstrated for actively multiplexing sensing uses. Moreover, the actively responding signals can directly drive optoelectronic

components for intuitive communication and be further processed for more sophisticated uses such as answering with sound, light, phrases, and so on. We believe the presented robotic skins that are self-powered, highly-sensitive, highly-stretchable can meet applications where soft interfaces are needed. And, the first achievements in the actively perceiving and responsive soft robots can push the boundaries of artificial intelligences, soft robotics, as well as their vast related applications.

[Ref]
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11:30 AM GI02.05.04
Enhanced Material Stiffness Change Using Low-Melting-Point Metallic Alloy Particle Additives Trevor L. Buckner[1], Rebecca Kramer-Bottiglio[1], Michelle C. Yuen[2] and Sangyup Kim[1]; [1]Yale University, East Hartford, Connecticut, United States; [2]Purdue University, West Lafayette, Indiana, United States.

Soft robots made from flexible and conformable materials face a major challenge resisting structural collapse or properly transferring forces when interacting with external loads. Without a permanent rigid support structure, soft robot design often turns to variable stiffness techniques that allow a robot to selectively generate rigid bones or soft joints as needed, thereby retaining the desirable properties of a soft robotic system while adding the ability to adapt to external obstacles and tasks as required. Many such solutions utilize stiffness-changing materials that soften or undergo a phase change with increasing temperature. In this talk we present a method of enhancing the range of stiffness change in these materials by introducing low-melting-point metallic alloy particles as an additive into the host material, specifically Field's metal embedded in an epoxy matrix. This method can drastically increase the stiffness of the rigid state, enhance the stiffness change of the host material phase transition due to particle jamming effects, and further decrease the final stiffness of the softened state by taking advantage of the solid-to-liquid transition of the particle inclusions. We will present a facile method for fabricating low-melting-point metal particles which improves upon existing techniques by scaling up batch size while maintaining control of particle size distribution. These particles will then be demonstrated as an additive in a conductive thermoset epoxy composite to enhance the stiffness change of that material. The effects of this additive on thermal and electrical material properties will also be presented. Finally, we will demonstrate the application of this variable stiffness material towards a soft robotic platform that can be continuously varied between compliant and load-bearing states.

11:45 AM GI02.05.05
Lightweight Multifunctional Structures for Next-Generation Robotics Monica Jung de Andrade; The University of Texas at Dallas, Richardson, Texas, United States.

Flexible, lightweight, multifunctional structures have a significant impact towards morphing technologies. In this work, we discuss some of the main techniques to fabricate fiber-like materials towards robotics. For instance, both infiltration and conformal deposition routes demonstrated the versatility of nanostructured nanotube based nanocomposites towards yarn-like actuators and flexible woven energy harvester. We demonstrated our silent, flexible, and tunable and scalable actuators can perform over thousands of cycles with negligible hysterisis. Finally, we demonstrated that fiber-like acuators have great potential towards lightweight and inexpensive orthotics, prosthetics and other tensegrity structures.

SESSION GI02.06: Variable Stiffness
Session Chair: Rebecca Kramer-Bottiglio
Tuesday Afternoon, November 27, 2018
Hynes, Level 1, Room 111

1:30 PM *GI02.06.01
Encoding Tissue Mechanics in Silicone Sergei S. Sheiko; Univ of North Carolina, Chapel Hill, North Carolina, United States.

Machines of the Future will synergize biomimetic mechanics with artificial intelligence. An ideal actuator should mimic muscle by being passively elastic while also efficiently converting potential energy into mechanical strokes. An ideal body material should mimic skin by being simultaneously compliant and strong to accommodate actuator motion. One drawback of biological tissues, however, is that their softness requires water, which is an unreliable engineering material. To overcome this challenge, we have developed a materials design platform that predicts mechanical properties of elastomers by engineering brush-like polymer networks Adaptable to any chemistry, the platform harnesses architectural parameters to encode tissue-mimetic softness, strain-stiffening, and extensibility within single-chemical-component systems. Applying this platform to archetypal poly(dimethylsiloxane) (PDMS), aka *silicone*, we have designed simultaneously supersoft and strain-stiffening elastomers without using solvent as a material "softener".

2:00 PM GI02.06.02
Variable Elasticity Silicone—Multifunctional Elastomeric Systems Enabled by Modulus Switching Michelle C. Yuen[1, 2], Trevor L. Buckner[2] and Rebecca Kramer-Bottiglio[2]; [1]Purdue University, West Lafayette, Indiana, United States; [2]Yale University, New Haven, Connecticut, United States.

Composite materials are greater than the sum of their parts – constituent materials work symbiotically to enhance the overall functionality of the composite. In this work, we create a new kind of silicone elastomer composite that can vary in its modulus of elasticity on demand. Our composite is made by embedding low melting point alloy (Field's Metal - FM) particles in a silicone elastomer matrix creating Field's Metal Silicone (FMSi). By applying heat to transition the FM particles between solid and liquid states, the composite can embody two different moduli of elasticity on-demand. In all cases, the composite remains "soft" – with a very low modulus (<10MPa) – but by changing its modulus, the silicone can fulfill different functions. Furthermore, by melting the FM particles, straining the bulk composite and then chilling the system, the shape of the deformed inclusions is fixed, holding the composite in a stretched state and adding anisotropy to the elastic modulus of the composite. This form of variable stiffness, (i.e. variable elasticity) has yet to be shown as a functional quasi-homogenous material, rather than a functional system constructed of discrete materials. We will present the fabrication of the FM particles and the composite; characterization of the FMSi over a range of particle loading fractions, temperatures, and deformations; and finally applications of the FMSi composite material in soft robotics.

2:15 PM GI02.06.03
A Stretchable Ionic Diode from Interpenetrating Polyelectrolyte Hydrogels Hae-Ryung Lee and Jeong-Yun Sun; Seoul National University, Seoul, Korea (the Republic of).

As the demand for soft and flexible devices steadily increases, the ionic applications demonstrated with gel materials have come under the spotlight. Here, stretchable ionic diodes (SIDs) made from polyelectrolyte hydrogels are introduced. Polyelectrolyte hydrogels were mechanically modified by methacrylated polysaccharides, forming interpenetrating networks (IPN) while preserving the ion-selectivity of poly(sulfopropyl acrylate) potassium salt (PSPA) and poly([acrylamidopropyl]trimethylammonium chloride) (PDMAPAA-Q). Then, SIDs composed of interpenetrating polyelectrolyte gels were fabricated in VHB™ substrates engraved by a laser. The SIDs showed rectifying behaviours under a maximum stretch of 3 and preserved their rectifications over hundreds of cycles. A wearable ionic circuit with LEDs operating during finger movements was also demonstrated as a corollary application of SIDs.

2:30 PM GI02.06.04
3D Printing of Liquid Crystal Elastomeric Actuators with Spatially Programmed Nematic Order Arda Kotikian[1], Ryan L. Truby[1], John W. Boley[1], Timothy J. White[2] and Jennifer Lewis[1]; [1]Harvard University, Cambridge, Massachusetts, United States; [2]Air Force Research Laboratory, Dayton, Ohio, United States.

Applications ranging from soft robotics to deployable devices would benefit from shape-morphing architectures that exhibit reversible, programmable actuation. Liquid crystal elastomers (LCEs) are of particular interest due to their intrinsic contractility, large deformations and high energy density. Here, we present a 3D printing method that enables one to pattern LCE inks with programmed director alignment in arbitrary form factors for use as artificial muscles. Specifically, we use high operating temperature direct ink writing (HOT-DIW) to align their mesogen domains along the direction of the print path. We then characterize their order parameter, actuation strain, and specific work. Using this process, we create shape-morphing LCE actuator (LCEA) architectures that undergo reversible planar-to-3D and 3D-to-3D' transformations on demand as well as 3D LCEAs (~1 mm thick) capable of lifting 233% more weight than other LCE actuators reported to date.

2:45 PM GI02.06.05
Zwitterions with Distinctive Stimuli-Responsive Behaviors to Construct Deformable Sensory Systems in Soft Robots Zhouyue Lei[1] and Peiyi Wu[1, 2]; [1]Department of Macromolecular Science, Fudan University, Shanghai, China; [2]Chemistry, Chemical Engineering and Biotechnology, Donghua University, Shanghai, China.

With growing interests in the fields of soft robots, it is crucial yet rather challenging to construct deformable sensory systems with customizable functionalities and human tissue-compatible mechanical properties. Herein, we design a type of zwitterions combining distinctive stimuli-responsive behaviors, i.e., both UCST (Upper Critical Solution Temperature) and LCST (Lower Critical Solution Temperature) by simply manipulating nano-level molecular dynamic interactions. It also integrates ultra-stretchability, high strength, impressive toughness, fatigue resistance, self-healability (at room temperature within 12 h) and facile processability (3D printing et al.), along with ionic conductivity for information transport. This material provides intelligent skins for soft robots and shows many advantages such as multiple sensations, tunable sensitivity, distinct visual effect (UCST and LCST) and adaptable mechanical properties. We believe this presentation is inspiring for the regulation of mechanical properties and stimuli-responsive behaviors in soft robots and we will also discuss the material design of artificial neuromuscular systems from the prespective of molecular dynamic interactions.

3:00 PM BREAK

SESSION GI02.07: 3D Printing
Session Chair: Bradley Nelson
Tuesday Afternoon, November 27, 2018
Hynes, Level 1, Room 111

3:30 PM *GI02.07.01
Liquid Metals for Soft Robotics Michael Dickey; North Carolina State University, Raleigh, North Carolina, United States.

This talk will discuss recent progress in utilizing liquid metals as conductors for stretchable, soft, and reconfigurable components for soft robotics. Alloys of gallium are noted for their low viscosity, low toxicity, and near-zero vapor pressure. Despite the large surface tension of the metal, it can be patterned into non-spherical 2D and 3D shapes due to the presence of an ultra-thin oxide skin that forms on its surface. Because it is a liquid, the metal is extremely soft and flows in response to stress to retain electrical continuity under extreme deformation. By embedding the metal into elastomeric or gel substrates, it is possible to form soft, flexible, and conformal electrical components, stretchable antennas, and ultra-stretchable wires that maintain metallic conductivity up to ~800% strain. Thus, these materials are well-suited for soft robotics because they decouple electrical conductivity and mechanical properties. In addition to introducing the advantages of these materials for soft robotics, this talk will focus on recent work to utilize liquid metal for (1) soft energy harvesting that converts mechanical motion to electrical energy, (2) tough energy absorbing materials, and (3) color changing materials for camoflage, strain sensing, and materials logic. These advances have implications for soft machines and robots that have ultra-soft mechanical properties.

4:00 PM GI02.07.02
Jet Based Electrochemical 3D Printing for Micromechanical Systems Realization Marco Stefancich[1], Harry Apostoleris[2, 3], Matteo Chiesa[2, 3] and Wael Othman[2]; [1]Dubai Electricity and Water Authority, Dubai, United Arab Emirates; [2]Khalifa University of Science, Technology and Research, Abu Dhabi, United Arab Emirates; [3]Fluid Metal 3D, Skien, Norway.

While laser based metal 3D printing is having a strong impact on the manufacturing sector, the lack of a low cost approach for this class of materials limits its further diffusion due to the high investment cost of the printer and the adjoining post-treatment equipment.
The realization of small scale mechanical systems, to enable next generation robotics, calls for different approaches capable of operating in the 10 to 1000 microns scale.
Multiple approaches are currently being proposed, among which we identify direct metal 3D printing by jet assisted localized electrochemical deposition as

a particularly promising one.
In its simplest form this approach is based on the use of a high speed electrolyte jet impacting on the intended deposition surface where a current, flowing through the jet, leads to the reduction of the metal ions to solid metal at the jet impact point.
The specific hydrodynamic properties of the jet ensure that the reduction is highly localized, potentially down to the microns scale, and its limited solely by the jet diameter. The deposition rate, moreover, largely exceeds those of conventional electrodeposition processes.
This approach allows metal deposition at room temperature without the need for controlled atmosphere and employing common water based electrolytic solutions with the use of simple hardware in a well understood process.
Due to the properties of the process, the deposition is also not limited to conductive substrates but can be extended to plastics without any pre-treatment as long as sufficient metal-plastic adhesion is achieved.
Here we discuss the fundamental physics and chemistry underlying the process and present the most current results on 3 dimensional structures in the mm scale realized in copper and nickel on conductive and non-conductive substrates.
Deposition rates of several microns/second are demonstrated and complex structures like micro-gears and free standing spirals are realized without the need for supporting structures.
This approach can be applied to the realization of complex mechanical micro devices to be used as platform for mm scale robotics systems.

4:15 PM GI02.07.03
Programmable Elasticity of Soft Materials Overcomes the Gauge Limit of Capacitive-Type Strain Sensor Young-Joo Lee, Seung-Min Lim, Jeong-Ho Lee, Sung-gyu Kang, Heung Nam Han, Jeong-Yun Sun, In-suk Choi and Young-chang Joo; Seoul National University, Seoul, Korea (the Republic of).

Soft and smart materials have been highlighted for providing intelligence to devices, i.e., soft robots, stretchable electronics, self-healing materials, camouflaging materials and so on. In this presentation, we will introduce a new soft material named 'auxetic elastomer', having unique elastic properties beyond the theoretical limit, by incorporating an auxetic frame within soft materials. Auxetic is known to be an open cell structure that can show negative Poisson's ratio. The elastic property of our auxetic elastomer can be predictively modulated by considering the auxetic geometry design and proper material selection. The experimental and simulation results proved that our continuum-solid auxetic elastomers can be designed to have negative in-plane and high positive out-of-plane Poisson's ratios, that cannot be achieved by conventional elastomers.
Incorporating the mechanical characteristics of the auxetic elastomer, we successfully overcome the electrical performance limit of a capacitive-type stretchable strain sensor in terms of sensitivity. Our sensor can show a gauge factor improved by 3.2-fold even maintaining the linear response. The sensor can be stretched up to 100 %, and show great cyclic durability. Our research has an originality in mechanical metamaterial research because it provides mechano-electric developments beyond convetional structural applications.

4:30 PM GI02.07.04
3D Fabrication of Fully Metallic Magnetic Microrobots Carlos C. Alcântara, Sangwon Kim, Bumjin Jang, Prakash Thakolkaran, Bradley Nelson and Salvador Pané; ETH Zurich, Zurich, Switzerland.

Small-scale robots have been proposed for a variety of medical applications, such as minimally invasive surgery, drug delivery, biopsy and diagnosis[1]. To transfer micro- and nanorobotic technologies to real clinical applications, approaches enabling the batch fabrication of micro- and nanoswimmers with biocompatible and biodegradable characteristics are necessary. Here, we present a process to manufacture arrays of fully metallic iron-based microrobots with complex features such as helices, double helices and spherical microscaffolds. The devices are fabricated by means of template-assisted electrodeposition (TAE) in 3D printed molds. The molds are obtained by two-photon polymerization (2PP). Compared to previous works with TAE and 2PP, our method is not restricted to the use of transparent conductive oxides (TCO) such as indium-tin-oxide[2-4]. While this substrate has been widely used to fabricate complex architectures with electrodeposition and 2PP, its conductivity is not optimal and can limit its use in other electrodeposition processes. Here, we show that we can print 3D molds on opaque conductive metallic substrates and overcome the limitations of TCO. With our approach, we demonstrate that Fe structures can be electrochemically grown with submicron lateral resolution and with a wide range of shapes and designs. The polymer templates can be prepared at a speed of ~5000 µm/s, with vertical dimensions ranging from 1.5 µm to 90 µm, while the length can be as large as 240 µm. Furthermore, mesoscale structures can be achieved by stitching segments along the XY plane. 3D iron microrobotic structures were further characterized in terms of locomotion with weak rotating magnetic fields (≤10mT) and in different fluids. Iron microhelices can perform corkscrew motion, while spherical microscaffolds can roll on surfaces. Interestingly, our microrollers exhibit a relatively high maximum forward velocity (v_{max}) of approximately 500 µm/s when manipulated in isopropyl alcohol. In silicone oil, the spherical rollers and the helices exhibit v_{max} values of 25 µm/s and 42 µm/s, respectively. Additionally, we demonstrate that the iron microhelices can swim against gravity and in three dimensions. Finally, preliminary degradation tests in simulated gastric acid at pH 1.7 show partial degradation of the helical structures.

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2. Gansel, J. K. *et al.* Gold helix photonic metamaterial as broadband circular polarizer. *Science* **325,** 1513–5 (2009).
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4. Wendy Gu, X. & Greer, J. R. Ultra-strong architected Cu meso-lattices. *Extrem. Mech. Lett.* **2,** 7–14 (2015).

4:45 PM GI02.07.05
3D Printed Biodegradable Microrobots for Theranostic Delivery Hakan Ceylan, Ceren Yasa and Metin Sitti; Max Planck Institute for Intelligent Systems, Stuttgart, Germany.

Untethered micron-scale mobile robots can leverage minimally invasive technologies by navigating and performing in hard-to-reach, confined and delicate inner body sites. Such a complex task requires integrated design and engineering strategies, where materials, powering, control, medical functionality and degradability need to be considered altogether. The present study reports a magnetically mobilized, locally responsive and biodegradable microrobotic swimmer for medical cargo delivery and release tasks. We design double-helical, hydrogel-based microswimmers, of 20 µm length, 3D-printed with complex geometrical and compositional features. At normal physiological concentrations, matrix metalloproteinase-2 enzyme can entirely degrade the microswimmer body in 118 h to solubilized non-toxic products. The amount of enzyme around the microswimmers tailors the release kinetics of the drug payload, and the drug bioaccessibility is eventually attained in full from the collapsed network of the microswimmers. Antibody-tagged iron oxide nanoparticles released from the degraded microswimmers serve for targeted labeling of SKBR3 breast cancer cells to realize the potential of medical imaging of local tissue sites following the therapeutic intervention. These results represent a leap forward toward clinical medical microrobots that are capable of sensing, responding to the local pathological information, and performing specific therapeutic and diagnostic tasks as orderly executed operations using their smart composite material architectures.

SESSION GI02.08: Poster Session: Materials for Robotics
Session Chairs: Donglei (Emma) Fan, Peer Fischer, Rebecca Kramer-Bottiglio and Bradley Nelson
Tuesday Afternoon, November 27, 2018
8:00 PM - 10:00 PM
Hynes, Level 1, Hall B

GI02.08.01
Graphene-Based Fiber for Artificial Muscle Hyunsoo Kim, Ji Hwan Moon and Seon Jeong Kim; Hanyang Univ, Seoul, Korea (the Republic of).

Artificial muscles are actively researched using various materials such as a polymer, carbon nanotube, and graphene for application to soft robotics or replacing motors. Especially, graphene-based actuators are attracted because of low cost and mass producible. However, previous graphene oxide (GO)-based actuators demonstrated torsional and bending actuations. Here, we developed a torsional and tensile actuating GO-based fiber for expansion of the application to various fields such as an artificial muscle, soft robotics, and indicators. The GO-based fiber was produced by wet-spinning technique with Nylon coagulation bath. This GO-based tensile actuator actuates reversible contraction and elongation without hysteresis by control the twisting direction of mandrel coils of GO-based fiber. Moreover, the GO-based actuator demonstrates lift load over 100 times heavier than itself, stable actuation and able to withstand high temperature over the melting point of the polymer. This novel kind of GO-based actuator, which has multi-directional actuation, have potential for a wide range of applications such as artificial muscles, robotics, and temperature sensing.

GI02.08.02
Algorithmic Stacking for Hyperform and Pluripotent Transformable Materials Yuki Lee[1], Young-chang Joo[1], Jyh-ming Lien[2] and In-suk Choi[1]; [1]Seoul National University, Seoul, Korea (the Republic of); [2]George Mason University, Fairfax, Virginia, United States.

Origami and *kirigami*, an art of paper folding, cutting, and transforming into a specific sculpture, are one of the innovative strategy for hyperform materials, which means scale-changeable materials from small to extremely large scale. In this study, we propose a novel algorithmic *kirigami* method that provides super compaction of an arbitrary 3-D shape, called “algorithmic stacking”. This super compacted structure can be manufactured in a workspace that is significantly smaller than the provided 3-D shape, by making the product a compacted state and converting it to the original 3-D shape. For example, even a product larger than 3D printer can be printed and used by the 3D printer. In addition, we have shown that the proposed stackable structures have high pluripotency and can transform into multiple 3-D target shapes. Our study includes voxelization for creating meshes, solutions for finding Hamiltonian path, mesh stripification, hinge design between adjacent meshes, and its application. Algorithmic stacking can give the solution for manufacturing products or devices in a limited workspace, make packing and transportation easier for a deployable application, and be a universal platform for pluripotent 3-D transformable structures.

GI02.08.03
Helical Nanomotors as Intracellular Probes Malay Pal[1], Neha Somalwar[1], Anumeha Singh[2], Ramray Bhat[3], Sandeep M. Eswarappa[2], Deepak K. Saini[3, 4] and Ambarish Ghosh[1, 5, 6]; [1]Centre for Nano Science and Engineering, Indian institute of Science, Bangalore, India; [2]Department of Biochemistry, Indian Institute of Science, Bangalore, India; [3]Department of Molecular Reproduction, Development and Genetics, Indian Institute of Science, Bangalore, India; [4]Centre for Biosystems Science and Engineering, Indian Institute of Science, Bangalore, India; [5]Department of Electrical Communication Engineering, Indian Institute of Science, Bangalore, India; [6]Department of Physics, Indian Institute of Science, Bangalore, India.

Cellular interior is a highly heterogeneous and anisotropic environment, whose physical, especially mechanical properties are difficult to measure. Currently, there are many efforts to develop techniques for such measurements, including atomic force microscopy, microplate, shear twisting cytometry, optical tweezers, optical stretchers, magnetic tweezers, particle tracking microrheology etcetera. Many of these techniques probe the cells from outside, and therefore not suitable for direct intracellular investigation as would be possible for probes maneuvered within the cellular interior. The purpose of this study is to develop a nanoprobe that can be manipulated inside the cell in a minimally invasive manner, with an extremely high degree of spatial accuracy at high speeds. As we show here, we have developed a helical shaped magnetic nanomotor, primarily made up of silica, polystyrene and iron, that can be internalized by the cells when incubated for around 24 hours. Subsequently, these internalized nanomotors can be actuated remotely inside the living cell by application of a rotating magnetic field created by a tri-axial Helmholtz coil. We will report various interesting observations regarding the motion of the motor, which proves how these tiny motors can promptly detect mechanical changes, that too with a micron scale resolution within a living cell. We believe this can lead to novel studies of the properties of the cellular interior at a single cell level and in future lead to various intracellular sensing and delivery applications.

GI02.08.04
Chemical/Light Powered Hybrid Micromotors with 'On-the-Fly' Optical Brakes Songsong Tang; Nanoengineering, University of California, San Diego, San Diego, California, United States.

Hybrid micromotors capable of both chemically-powered propulsion and fuel-free light-driven actuation and offering built-in optical brakes for chemical propulsion are described. The new hybrid micromotors are designed by combining photocatalytic TiO_2 and catalytic Pt surfaces into a Janus microparticle. The chemical reactions on the different surfaces of the Janus particle hybrid micromotor can be tailored by using chemical or light stimuli that generate counteracting propulsion forces on the catalytic Pt and photocatalytic TiO_2 sides, respectively. Such modulation of the surface chemistry on a single micromotor leads to switchable propulsion modes and reversal of the motion directionality that reflect the tuning of the local ion concentration and hence the dominant propulsion force. An intermediate Au layer (under the Pt surface) plays an important role in determining the propulsion mechanism and operation of the hybrid motor. The built-in optical braking system allows ‘on-the-fly’ control of the chemical propulsion through photocatalytic reaction on the TiO_2 side to counterbalance the chemical propulsion force generated on the Pt side. The adaptive dual operation of these chemical/light hybrid micromotors, associated with such control of the surface chemistry, holds considerable promise for designing smart nanomachines that autonomously reconfigure their propulsion mode for various on-demand operations.

GI02.08.05
Urease-Powered Nanomotors for Enhanced Anticancer Drug Delivery Ana Hortelão[1], Tania Patiño[1], Rafael Carrascosa[1] and Samuel Sanchez[1, 2]; [1]Institute for Bioengineering of Catalonia (IBEC) The Barcelona Institute of Science and Technology, Barcelona, Spain; [2]Institució Catalana de

Recerca i Estudis Avancats (ICREA), Barcelona, Spain.

Urease-Powered Nanomotors for Enhanced Anticancer Drug Delivery

Micro- and nanomotors are structures capable of self-propulsion in fluids,[1] which have been considered interesting for biomedical applications, such as the active transport and delivery of specific drugs to the site of interest.[2] Here, we present the loading of urease-powered nanomotors with the anticancer drug Doxorubicin, as well as the substrate-dependent (urea) drug release and efficient delivery to cells.[3] These nanomotors are based on mesoporous silica core-shell nanoparticles functionalized with urease enzyme. The motion dynamics of these self-propelled silica nanomotors was analyzed using optical tracking and dynamic light scattering. A four-fold increase in Doxorubicin release is achieved by nanomotors after 6 hours exposure to urea, compared to nanomotors in passive conditions (absence of urea).
Moreover, active Doxorubicin-loaded nanomotors present an enhanced anticancer efficiency toward HeLa cells, that arises from a synergy between increased drug release and production of ammonia during catalysis. We found that in the presence of urea, Doxorubicin-loaded nanomotors exhibit improved effect on HeLa cells compared to passive carriers, where a higher content of Doxorubicin is uptaken after 1, 4, 6, and 24 hours incubations. Naturally high urea concentrations present in bladder can trigger the motion of anticancer drug loaded nanomotors. This effect generates a more effective drug release, which can be of particular interest for intravesical drug delivery. As a step forward, urease-powered nanomotors, coupled with an antibody, are being developed to target bladder cancer derived from transitional cell papilloma. The improvement in drug delivery efficiency achieved by enzyme-powered nanomotors may hold potential toward their use in future varied applications, such as the substrate-triggered release of drugs in precise locations.

(1) Katuri J, Ma X, Stanton MM, Sánchez S. Designing Micro- and Nanoswimmers for Specific Applications. *Acc Chem Res*. **2017**; 50(1):2–11
(2) Ma X, Wang X, Hahn K, Sánchez S. Motion Control of Urea-Powered Biocompatible Hollow Microcapsules. *ACS Nano*. **2016**; 10(3):3597–605.
(3) Hortelao, A C; Patiño, P; Perez-Jimenez, A; Blanco, A and Sanchez, S *Adv. Funct. Mater.* **2017**; 1705086

GI02.08.06
Highly Increased Output Voltage with Diverse Textiles in Triboelectric Nanogenerators for a Wide Variety of Soft Robot Application Jae-Bum Jeong[2], Swarup Biswas[1], Suwoong Lee[2] and Hyeok Kim[1]; [1]Gyeongsang National University, Jinju, Korea (the Republic of); [2]Korea Institute of Industrial Technology, Daegu, Korea (the Republic of).

Triboelectric nanogenerator (TENG) with fabrics has been widely studied due to its potential application in smart textiles, so to be used to wearable electronics. The surface property of fabric affects on the output voltage of TENG because the surface charge density depends on the kind of fabrics. We demonstrate the enhanced output voltage of TENG with a variety of textiles. Elastomer was inserted to support between Cu electrodes. In this process, various fabrics, such as cotton, rayon, wool, acetate, silk, nylon, and acryl, were covered the elastomer to control surface charge. The output voltages were measured by changing surface frictional charge density. The change of output voltage according to frictional electrostatic voltage from 3 V to 25 V is demonstrated. In addition, effect of the moisture regain of various textiles on output voltage is also studied.

GI02.08.07
Metal-Oxide Based Micromotors for the Removal of Organic Pollutants and Heavy Metals Diana Vilela[1], Jemish Parmar[1], Katherine Villa[1] and Samuel Sanchez[1, 2]; [1]Institute for Bioengineering of Catalonia, Barcelona, Spain; [2]Institute for Research of Catalonia (ICREA), Barcelona, Spain.

Water contamination is one of the most persistent problems in public health. Micromotors can act as an efficient tool for water remediation because of the enhance mass transfer by active motion. Bubble-propelled micromotors move due to the bubble-recoil mechanism, which are associated to micro/mixing capabilities, resulting in a potential platform for water remediation applications. The choice of the functional material on the micromotors surface depends on the target pollutants. However, several challenges must be addressed before micromotor-based water treatment technology can be used in practical applications, such as the high cost associated with the use of Pt for propulsion. Moreover, these micromotors are typically fabricated by expensive techniques such as, rolled up technology[1] or electrodeposition methods[2]. In order to obtain efficient and inexpensive micromotors for water treatment, we described cobalt ferrite ($CoFe_2O_4$)[3] and Fe_2O_3-decorated SiO_2/MnO_2 micromotors fabricated[4] by facile and scalable synthesis methods, respectively.

The $CoFe_2O_4$ micromotors were fabricated by agglomeration of dried $CoFe_2O_4$ nanoparticles (NPs), which were previously synthesized via solvothermal route using Co^{2+} and Fe^{3+} salts as precursors in ethylene glycol. These micromotors, self-propelled without the need of a surfactant, carried out an efficient removal of tetracycline antibiotic from wastewater and, after the reaction was complete, were collected and separated using their magnetic properties. In addition, we proved that $CoFe_2O_4$ micromotors enhanced the production of hydroxyl radicals *via* Fenton-like reaction due to the presence of cobalt.

The γ-Fe_2O_3-decorated SiO_2/MnO_2 micromotors consisted of mesoporous silica-based microjets with MnO_2 immobilized on the inner surface and decorated with γ-Fe_2O_3 NPs on the outer surface. They were synthesized by growing silica tubes on a polycarbonate template by sol-gel method[5] and immobilizing MnO_2 and γ-Fe_2O_3 catalysts. The inner layer of MnO_2 act as functional material for both propulsion and removal of pollutants and γ-Fe_2O_3NPs as photocatalytic, adsorptive and magnetic material. Thus, these micromotors enabled the efficient degradation of organic pollutants (dyes and antibiotics) under visible light irradiation, as well as the removal of heavy metal ions. Regarding their magnetic properties, they were magnetically steered facilitating their recovery and further reuse.

Therefore, these approaches open up new inexpensive alternative methods to fabricate other types of metal-oxide based micromotors for different applications in the environmental field.

[1] Parmar et al. Adv. Funct. Mater. 26 (2016)4152-4161
[2] Vilela et al. Nanoletters 16 (2016)2860-2866
[3] Parmar et al. Appl. Mater. Today 9(2017)605-611
[4] Villa et al. ACS Appl. Mater. Interf. (2018)10.1021/acsami.8b04353
[5] Vilela et al. Nanoscale 9(2017)13990-13997

GI02.08.09
Development of Seamless Soft Actuators Applied as a Robotic Assistive Device and Teaching Tool in Art Studios Edward King, Aditya Sardesai, Ruhao Sun, Bram Schork, Yiheng Chen, Holly Golecki, Elijah Lee, Josiah Somani, Alexander Greer, Daniel Chow, Calvin Costner, Troy Barnes, Bryce Broadus, Biagio DiSimone, Safa Obuz, Toby Ma, Yeshwin Sankuratri and Robert Esgro; The Haverford School, Haverford, Pennsylvania, United States.

The nature and age of the soft robotics field, presents the potential for expansive growth. Exposing secondary school students to this rapidly growing field allows for development of the soft robotics industry in new and imaginative ways. High school students can engage in materials-based research through the

Soft Robotics Toolkit. During the process of fabricating pneumatic actuators, we reasoned that new fabrication techniques may make actuator production easier and more accessible to young students. Traditionally, a two part mold has been used to create simple soft robotic actuators. In order to increase the durability of the actuator, we set out to design a new, single-mold system made from common household materials. Through the Soft Robotics Toolkit Design Competition hosted by Harvard University, our team ranging in age from 14-18 years developed a novel process of actuator fabrication by utilizing a range of dissolvable materials to create intricate internal structures. We believe that this single pour method will eliminate the reoccurring problem of the two-part molding system, delamination. First, internal structures were hand-cut from polystyrene and submerged in silicone during molding. After curing, acetone was used to dissolve the internal structure and air was pumped into the same access port to pneumatically actuate the device. To improve upon the reproducibility of actuator production, we explored dissolvable materials that can be 3D printed: polyvinyl alcohol (PVA) or acrylonitrile butadiene styrene (ABS). To investigate mechanical changes in actuation, geometries of the internal structures were varied. Solubility studies and dynamic actuation testing were used to evaluate each new material for its precision and ease of manufacturing. This new method was also applied to our previous work on edible actuators, creating internal structures from sugar, solving a functional drawback of that work, delamination. After developing seamless silicone actuators, they were applied in a glove. In collaboration with an art teacher at our school, we developed a method to transfer nuanced hand motions used to throw pottery from an expert to a novice artist. The seamless actuators proved to be robust in this dynamic environment. The development of the King Actuators was an entry in the High School Division of the 2018 Soft Robotics Toolkit Design Competition. Seamless soft robotic actuators used to teach the art of throwing pottery, created by high school students, shows the applicability of the Soft Robotics Toolkit for secondary STEM education and outreach. Making students aware of what is possible through projects like this will inspire the next generation of innovators in materials science and robotics. This presentation will discuss the technical merits of the work as well as the benefits to outreach. The team’s submission can be viewed here: https://vimeo.com/274309325

GI02.08.10

Self-Regulation in Plant Robots—Embedded Intelligence Through Non-Equilibrium Material Feedback Bilge Baytekin[1, 2], Doruk S. Cezan[1] and Hasan T. Baytekin[2]; [1]Chemistry Department, Bilkent University, Ankara, Turkey; [2]National Nanotechnology Research Center (UNAM), Bilkent University, Ankara, Turkey.

Self-regulation through non-equilibrium feedback systems is a vital feature of living organisms. Strategies to design new sensing and actuation mechanism for new generation robots may benefit from this interesting feature. However, implementation of this idea in artificial systems and robots is hampered by the complex nature of self-regulation event. Nevertheless, with the correct choice of materials and material-feedback, one can successfully achieve such a bioinspired self-regulated robot. Here we show, simple systems in which plant robots and/or artificial plant parts can be actuated by artificial self-regulation and display ‘embedded intelligence’ through autonomous operation. We especially choose plants as our source of bioinspiration (despite the common trend in bioinspired robotics in favor of animals) for their amazingly versatile sensing and motion features - two of which are heliotropism (tracking of the sun) and nyctinasty (opening and closing of the leaves upon presence/absence of light). In our systems, we mimic these two features through thermoresponsive material-feedback by shape memory alloys (SMAs) and hydrogels. In the first systems with SMAs, we see an increase in the energy harvesting efficiencies of 120% through material feedback. In the second system, where a true biomimetic nature is attained by the additional artificial transpiration ability, the system not only displays similar autonomous heliotropic and nyctinastic behavior but also can be manipulated for desired geometry, material, and chemistry. In both kind of systems, we have shown that implementing material-feedback into robots achieves embedded intelligence in them, which can be beneficial in terms of energy saving and achieving living-like behavior in new generation robots.

GI02.08.11

Red Blood Cell-Based Soft Microrobots Powered by Bacteria Yunus Alapan[1], Oncay Yasa[1], Oliver Schauer[2], Joshua Giltinan[1], Ahmet Tabak[1], Victor Sourjik[2] and Metin Sitti[1]; [1]Max Planck Institute for Intelligent Systems, Stuttgart, Germany; [2]Max Planck Institute for Terrestrial Microbiology, Marburg, Germany.

Red blood cells (RBCs) constitute more than 90% of cells in the blood stream and are uniquely specialized to carry maximum loads by losing their nuclei through maturation. RBCs can deform and squeeze repeatedly without blocking any capillaries that can be as small as half of their diameter. Due to their abundancy and affordability, RBCs represent the most feasible and high-throughput personalized carriers for cargo delivery. Despite these advantages, RBCs as cargo carriers are passive delivery agents that are limited by poor targeting as similar to conventional drug delivery vehicles. On the other hand, bacteria-powered biohybrid microrobots have recently shown to actively transport and deliver cargoes encapsulated into their synthetic constructs to specific regions locally. However, use of synthetic materials as cargo carriers can result in inferior performance in load-carrying efficiency, biocompatibility, and biodegradability, impeding clinical translation of biohybrid microswimmers.

We have developed a bacteria-powered biohybrid microrobot using RBCs as autologous cargo carriers for active and guided cargo delivery. RBCs were loaded with anti-cancer doxorubicin drug molecules (DOX) and superparamagnetic iron oxide nanoparticles (SPIONs) and functionalized with biotinylated anti-TER-119. Multifunctional biohybrid microrobots were fabricated by attachment of RBCs to bioengineered motile bacteria, Escherichia coli MG1655 expressing biotin attachment peptides, via biotin-avidin-biotin binding complex. Release of DOX molecules from RBC cargoes was investigated over 120 hours at different pH conditions (3.1 - 9.2) and enhanced release rates were observed at low pH conditions. Autonomous and on-board propulsion of biohybrid microrobots was provided by bacteria (~10 μm/s), and their external magnetic guidance was enabled by SPIONs loaded into the RBCs. Moreover, bacteria-powered RBC microrobots displayed preserved deformability and attachment stability even after squeezing in microchannels smaller than their sizes, as in the case of bare RBCs. Inherent compliance of RBCs further allowed active deformation and passage of RBC microswimmers through confined spaces only by means of bacterial propulsion, while preserving their motility. In addition, an on-demand light-activated hyperthermia termination switch was engineered for RBC microswimmers to control bacteria population after targeted operations.

RBCs, as biological and autologous cargo carriers in the biohybrid microswimmers, offer notable advantages in stability, deformability, biocompatibility, and biodegradability over synthetic cargo-carrier materials. The biohybrid microswimmer design presented here transforms RBCs from passive agents into autonomous, active, and guidable cargo carriers toward targeted drug and other cargo delivery applications in medicine.

GI02.08.12

Controllable Dynamic Self-Assembly of Mobile Microrobotic Swarms with Programmable Interrobotic Interactions Berk Yigit, Yunus Alapan and Metin Sitti; Max-Planck Institute for Intelligent Systems, Stuttgart, Germany.

Microrobotic swarms are indispensable for amplifying throughput in high-impact microrobotic applications for targeted drug delivery, medical diagnostics, parallel micromanipulation, and environmental sensing and remediation. Bottom-up assembly approaches present facile means for fabrication of microrobot swarms, owing to their parallel assembly capabilities and reconfigurability enabled by modular constituents. Previous studies showed that single microrobots of controlled size, shape, and function can be formed by dynamic self-assembly of magnetic microparticles. However, their controlled fabrication and operation at high densities has remained a challenge as they are susceptible to coalescing into poorly-defined aggregates due to unintended magnetic dipolar attractions.

Here, we show that controlling magnetic interactions via precessing magnetic fields enable massively parallel formation and operation of mobile

microrobotic swarms at high densities, with well-defined microrobot morphologies, locomotion characteristics and spatial order. Starting from a dispersed suspension of superparamagnetic particles over a planar substrate, we use precessing magnetic fields (dynamic rotating and static unidirectional fields) to form a swarm of linear chain assemblies, each consisting of 3 to 5 superparamagnetic particles. These chain microrobots locomote on surfaces by applying a tilt to their precession axis. Control over the angles of precessing magnetic field allows tuning magnetic interactions among microrobotic chains from attractive to repulsive. Utilizing unidirectional repulsive interactions that prevent aggregations in the plane of the substrate, we show that microrobots are able to maintain structural and functional integrity over macroscale distances (~1 cm), even in highly compacted swarms travelling through narrow passages. Moreover, interrobotic interactions enabled control over collective order for achieving a homogeneous spatial distribution and a narrow distribution of nearest neighbor distances indicating spatial organization. These swarms can further achieve directional transport of large cargoes on surfaces and small cargoes in bulk fluids.
Our results demonstrate that interrobotic interactions are crucial for operation of dynamically self-assembled microrobots without forming aggregates at high densities, and enables controlling collective order inside microrobotic swarms. Overall, described design approach, exploiting physical interactions among individual robots, enables facile and rapid formation of self-assembled and reconfigurable microrobotic swarms with programmable collective order.

GI02.08.13
Algal Microswimmers for Cargo Delivery Oncay Yasa, Pelin Erkoc, Yunus Alapan and Metin Sitti; Max-Planck Institute for Intelligence Systems, Stuttgart, Germany.

Nature exhibits intriguing microscopic swimmers with innate energy harvesting abilities from their local environments. Use of natural swimmers as delivery agents presents an alternative platform to transport cargoes inside the body. Their small sizes and intrinsic properties could allow deep tissue penetration, and in this way, to reach difficult-to-access inner body locations. Although bacteria are heavily utilized as actuators in biohybrid microswimmer design for cargo delivery applications, their acute pathogenicity along with rapid growth in physiological conditions limit their clinical applications to inner body cavities and solid tumors, and necessitate search for an agile biological swimmer with better biocompatibility, such as microalgae. Microalgae, eukaryotic microswimmers with a facile culture process, present high propulsion (> 100 µm/sec), autofluorescence and phototactic guidance capabilities. *Chlamydomonas reinhardtii* [*C. reinhardtii*], as a unicellular biflagellate microalga species, has been barely explored as an actuator to fabricate biohybrid microswimmers for biomedical applications, mainly due to its inefficient motility inside typical cell culture media such as minimum essential medium with phenol red.

We developed a biocompatible microswimmer, powered by a unicellular freshwater green microalga, by integrating polyelectrolyte [PE] functionalized magnetic spherical polystyrene [PS] (1 µm in diameter, 20% iron oxide content) cargoes onto the surface of *C. reinhardtii* through non-covalent electrostatic interactions. The integration using electrostatic interactions allowed non-invasive and facile fabrication of the biohybrid algal microswimmers without the requirement for any harsh chemical reaction. PE functionalized microparticles were alternatingly fabricated with oppositely charged poly(allylamine hydrochloride) (positively charged) and poly(sodium 4-styrenesulfonate) (negatively charged) polyelectrolytes using layer-by-layer deposition technique. The fabrication of the microparticles was finalized at the 5th layer with the positively charged PE to allow electrostatic interaction of the microparticles with the negatively charged microalgae. Initially, interaction of the microalgae with PE functionalized surfaces was characterized using quartz crystal microbalance with dissipation monitoring. Then, three-dimensional swimming motility of the constructed biohybrid algal microswimmers was characterized in the presence and absence of a uniform magnetic field (in *x*-direction) using a transmission digital holographic microscope. Finally, motility of the microalgae was investigated in different biological media, and a model drug, fluorescent isothiocyanate-dextran (a water-soluble polysaccharide) molecule, was delivered to mammalian cells.

To conclude, we demonstrate a biocompatible algal microswimmer which can be utilized, as an alternative to bacterial microswimmers with superior properties, in various biomedical applications.

GI02.08.14
Recent Advances in the Powering and Actuation of Nanorobots Using Sound Waves Fernando Soto and Joseph Wang; Nanoengineering, University of California, San Diego, La Jolla , California, United States.

Micro and nanoscale robots consist of microscopic mobile devices that can convert local chemical fuels or external inputs into autonomous propulsion. These small-scale tools can perform multiple tasks while propelling in solution, as their motion allows them to transport cargo or reactive materials, increase recognition events and induce fluid mixing. Such functionality could lead to the improvement in human health and disease treatment. Despite the attractive performance and autonomy of chemically-powered nanomotors, they still present limitations that warrant pursuing alternatives. Specifically, these catalytic microrobots have short life spans or require toxic fuels to operate, and their swimming behaviour is commonly hard to modulate. On the other hand, recently introduced acoustically-powered motors make use of acoustic fields sound waves that are relatively innocuous and easy to manipulate, offer unique advantages for enabling efficient and controllable motion (in different biological media), and allow for diverse surface functionalization.

Here, I will present recent advances in the desing, powering, actuation and aplication of ultrasound-based nanorobots. Including the use of ultrasound-propelled asymmetric nanostructures, which have been translated towards various biomedical concepts including targeted drug delivery, bacteria and toxin capture, and intracellular drug delivery.[1,2] The use of ultrasound fields to modulate the propulsion and collective behaviour of chemically propel micro-engines.[3,4] New tools for nanosurgery which consist on ultrasound triggered microcannons, capable of firing nanobullets and penetrate tissue, [5,6] and ultrasound powered automated assembly lines capable of manipulating and isolating particles and live cells[7].

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GI02.08.15

Light-Driven Cyanamide Functionalized Polyheptazine Imide Based Janus Microswimmers and Its Applications Varun Sridhar[1], Filip Podjaski[2], Julia Kröger[2], Bettina Lotsch[2] and Metin Sitti[1]; [1]Max Planck Institute for Intelligent Systems, Stuttgart, Germany; [2]Max Planck Institute for Solid State Research, Stuttgart, Germany.

Light-driven microswimmers have garnered attention for their potential use in various applications such as environmental remediation, hydrogen evolution, and targeted drug delivery. In this work we present a Cyanimide functionalized polyheptazine imide polymer (NCN) based light-driven microswimmer. We demonstrate microswimmers with different Janus cap structures (Pt, Au and Co). The microswimmers move due to self-electrophoresis when UV light is incident on them. The microswimmers show enhanced swimming speeds on addition of alcohols like methanol and H_2O_2 under low-intensity ultraviolet (UV) light. They also exhibit phototactic behavior when light is incident on them. These microswimmers are also made steerable by using a thin Co magnetic layer. They can be used in potential energy storage and hydrogen evolution experiments. The microswimmers show increased catalytic activity due to their active motion, causing higher intermixing of the solution resulting in increased hydrogen evolution. NCN has the ability to create, store and release charges on demand, enabling propulsion even without light. Their porous structure and inherent fluroscence is beneficial for future potential applications such as biosensing, selective heterogeneous photocatalysis, and targeted cargo delivery.

GI02.08.16

Integrated Materials Framework for Untethered Soft Robotics Xiaonan Huang[1], Kitty Kumar[1], Mohammad K. Jawed[1], Amir Mohammadi Nasab[2], Zisheng Ye[1], Wanliang Shan[2] and Carmel Majidi[1]; [1]Carnegie Mellon University, Pittsburgh, Pennsylvania, United States; [2]University of Nevada, Reno, Reno, Nevada, United States.

In order to approach the maneuverability of natural organisms, soft robots must be capable of locomotion without reliance on bulky external mechanical hardware or power supplies. Achieving this untethered functionality requires careful selection and integration of actuators, circuitry, control electronics, and on-board power. We demonstrate this with an integrated materials architecture that enables the creation of a wide variety of untethered soft robots. In this presentation, we will present the materials framework and show its applications to walking, crawling, and rolling soft robots. We will focus particular attention on an untethered soft palm-sized, 25g “electronic soft robot” quadruped that is capable of “biologically-relevant” walking speeds that approach those observed in natural organisms of similar size. The robot is composed of a flexible printed circuit board that integrates power and control electronics and electrically-powered soft limbs that contain shape memory alloy (SMA) wires sandwiched between a non-stretched and pre-stretched layer of soft, thermally-conductive elastomer. It is versatile and robust and has the capability of walking on a variety of surfaces, including up inclines, rocky terrain and poppy seeds, climbing over a half body height step, and maintaining continuous forward locomotion through confined space or after being dropped from an elevated height. In addition to these locomotion studies, we perform a combination of experimental and computational analyses that relate limb bending curvature, flexural stiffness, and blocking force with various material parameters and operational conditions. Such characterization provides a framework for the design and operation of untethered soft robots that move using SMA-actuated limbs.

GI02.08.17

A Roadmap Towards Peano-HASEL Actuators with Drastically Improved Performance Nicholas A. Kellaris[1, 2], Vidyacharan Gopaluni Venkata[1] and Christoph Keplinger[1, 2]; [1]Department of Mechanical Engineering, University of Colorado Boulder, Boulder, Colorado, United States; [2]Materials Science and Engineering Program, University of Colorado Boulder, Boulder, Colorado, United States.

Traditional robots – made from electric motors and gears – are noncompliant, complex, and bulky, which limits their ability to perform in unstructured environments and increases risk during human-robot interactions. As a result, there have been efforts to design actuators from soft, compliant materials for use in versatile and adaptable robots. Electrohydraulic Peano-HASEL (Hydraulically Amplified Self-healing ELectrostatic) actuators have shown promise as linearly contracting soft actuators with high-speed operation, scalability, and simple design. Coupled with their versatility in fabrication and materials, Peano-HASEL actuators have broad potential in robotic systems.

To elucidate fundamental actuation characteristics of Peano-HASELs, we present a model that predicts the quasi-static behavior and scaling laws of these actuators without using any fitting parameters. We provide extensive experimental validation of this model using actuators constructed from heat-sealable biaxially-oriented polypropylene, and find robust agreement with only a simple set of geometric assumptions. From these results, we identify several straightforward methods for tuning and improving the performance of Peano-HASELs – including the creation of actuators optimized for maximum strain or maximum force, and a method for drastically improving the specific energy of these devices. Further, we experimentally demonstrate actuators with increased specific energies following the predictions of these modeling results. Moving forward, these results will serve as a roadmap for the development of Peano-HASEL actuators with superior performance, opening new applications for robots using artificial muscles.

GI02.08.18

A Tri-Modal One-Layer Tactile Sensor for Augmenting Robotic Grasping Caroline Yu[1], Jaylene Salas[2] and Ioannis Kymissis[1]; [1]Columbia University, New York, New York, United States; [2]The City College of New York, New York, New York, United States.

Stable robotic grasping consists of robotic structures estimating an object’s location and shape then grasping and holding the object without slipping. Currently, various sensing modes are used to estimate the object’s location and shape, including image detection and applied force detection. Dang and Allen (2013) demonstrated stable grasping using tactile sensing data. The support vector machine classifier distinguished stable and unstable grasps with an accuracy of 81% [1]. In this work, we are proposing to improve the classifier’s accuracy by wrapping three sensing modes around a robotic finger. Because multimodal tactile sensors are typically large or not form-fitting, flexible tactile sensors can be used for absolute and relative force measurements, including multimodal polymer-based sensing skins [2][3]. This work presents the material processing and device performance for three sensing modes on a thin flexible PVDF layer. Polyvinylidene fluoride (PVDF) is a piezoelectric polymer used for relative movement tactile sensing [4][5]. One side of the PVDF layer has photolithographically-defined silver circular electrodes. The other side of the PVDF layer has photolithographically-defined silver serpentine-structured strain gauges aligned with the back-side electrodes. The aligned features enables localized measurements. Relative movement is sensed by measuring the change in charge between overlapping silver traces. Applied force is sensed by measuring the change in resistance of the strain gauges. Object proximity is measured using the strain gauge traces for capacitive coupling sensing. Uniform force was applied using an Admet eXpert 5600 testing machine to measure applied force limits. The device tracks impulse responses from applied forces between 0.5 to 20 N. Bending induced tensile strain and compression were applied to the device using arcs of various radii. The silver strain gauges have an expected gauge factor of 2.83 and tracks change in resistance down to 4 % bending induced tensile strain. Capacitive readings can measure metallic objects up to 20 cm away from the sensor layer. The piezoelectric and capacitive sensing modes were tested on the fingers and palm of a robotic Barrett Hand. Testing results demonstrate that sensing measurements can be used to enhance stable grasping estimations.

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GI02.08.19

3D Bioprinting of Adaptative Biological Actuators Based on Skeletal Muscle with Controllable Shape, Alignment and Contractility Tani Patino, Rafael Mestre, Xavier Barcelo and Samuel Sanchez; Institute for Bioengineering of Catalonia, Barcelona, Spain.

Current robotics systems are facing many challenges in a world that requires them to adapt to different environments and interact with humans and other living organisms. For this reason, many recent advances in material science have opened up the possibility of combining biological systems with artificial materials to obtain hybrid bio-robotic devices that can offer complex capabilities, like self-healing, high adaptability and response to different stimuli.[1] Several groups have developed hybrid bio-actuators based on cardiac[2] and skeletal muscle cells,[3] which, in particular, have shown three-dimensional architectures and some of the commented complex behaviours.

In parallel, the 3D bioprinting technique has emerged as a powerful tool for the development of functional three-dimensional tissues.[4] Although 3D printing of artificial materials has been used to fabricate scaffolds or molds for hybrid bio-actuators, 3D bioprinting of skeletal muscle tissue, together with soft skeletons, has not been reported in the field of hybrid bio-robotics. Here, we present our recent advances in the fabrication of 3D bioprinted hybrid bio-actuators based on skeletal muscle tissue, taking advantage of the unique versatility, rapid-prototyping and simplicity of the technique. We report a full characterization and optimization of the printing from the material point of view, but also paying special attention to the biocompatibility, as well as differentiation and maturation of cells inside the bioprinted hydrogel. Furthermore, we demonstrate myotube alignment, following the direction of printing, by immunostaining and scanning electron microscopy. This result is a unique consequence of the use of 3D bioprinting that is typically difficult to achieve by other means. Finally, we take advantage of the multi-material printing capabilities of the technique to 3D bioprint a hybrid biological actuator whose contractions can be completely controlled by external electric fields. We prove the adaptability of the hybrid bio-actuator applying different training protocols at different frequencies, resulting in a modulation of the force and the relative expression of related proteins.

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GI02.08.20

Autonomous, Microfluidic Chemical Gait Generation at the Micronscale Ian Hunter, Mike Norton and Seth Fraden; Brandeis University, Waltham, Massachusetts, United States.

Living beings have evolved to use coupled neurons to perform autonomous functions, from breathing to walking. It is known local, often small, clusters of neurons (CPGs) perform these essential functions, in the absence of input from the brain. This modular method of control of whole organisms may present advantages over centralized, computational robotic control. An experimental platform, composed of diffusively-coupled PDMS microreactors each containing the oscillatory, light sensitive Belousov-Zhabotinsky (BZ) chemical reaction has been developed. This method allows rapid testing of methods of CPG design out of coupled oscillators. Further it will aid the design of already existent micronscale, hydrogel robotics through revealing how control of diffusive fluxes within a patterned hydrogel could result in different spatiotemporal patterns of actuation. Experimental observations of quadruped gaits in 4 reactors, and a categorization of both individual, and pairs of reactors within the system will be the focus of the presentation.

GI02.08.21

A 3D-Printed-Layered Module of Compliant Electrostatic Gripper Consisting of Elastically Deformable Bipolar Micro-Probes for Manipulation of Thin Film/Textile Objects Shigeki Saito, Kenta Kudo and Kunio Takahashi; Tokyo Institute of Technology, Tokyo, Japan.

For the future robotics in many industries, we propose a new concept of compliant electrostatic gripper by stacking 3D-printed-layered modules that consist of elastically-deformable bipolar micro-probes. Due to the module structure, the micro-probe tips can be aligned precisely on the large surface area where the electrostatic force is generated by the bipolar electrodes. The proposed gripper is expected to work effectively on thin film/textile objects with compliance on the surface without any damage due to excessive stress. The module is prototyped by 3D printer, and the performance as a reliable holding/detaching gripper by electrostatic force is experimentally evaluated.
To date, new handling techniques of thin film/textile materials such as polymer films, papers, and fabrics have been required in order to develop advanced wearable devices, and many other applications, although the conventional electrostatic chucks work successfully typically for flat and hard wafer in the semi-conductor fabrication. In recent years, our research group has been developing compliant bipolar electrostatic grippers through the past studies. Still the critical issue remains to be solved that the effective area for electrostatic force should be enlarged while the spatial density of bipolar electrodes should be increased. In addition, the insulation between the bipolar electrodes is seriously important to avoid the damage from the breakdown in case of spatially high density of electrodes. To solve this issue by layer-by-layer fabrication, 3D printing technology can be considered one of the most useful for applications in relatively large scale.
The module having bipolar probes consists of three-sublayer (conductor-insulator-conductor) structure. The 80mm-long bipolar probes are arranged at 45-degrees to interface. The dimensions of a rectangle tip surface of the bipolar probes are 1.2mm in width and 1.6mm in height. Conductive and insulating layers are 0.4mm and 0.8mm in thickness, respectively. The bipolar probes are fabricated by a fused deposition modeling (FDM) 3D printer having a 0.4mm-diameter nozzle. Carbon-mixed and ABS filaments are used for conductor and insulator, respectively.
The force curve is experimentally determined to evaluate the compliance, the maximum attractive force, and other characteristics. Additionally pick-and-place demonstrations for a PP film, a printing paper and a fabric are conducted to show that the module work as a handling/detaching device for thin film/textile objects under particular conditions. Furthermore, even if the influence of residual charge is not negligible due to the applied voltage, the detachment is always successful with an appropriate tilt angle that causes peeling effect in the contact interface between probe tips and objects. Therefore the proposed concept will highly contribute to the fabrication technology in the next-generation robotics.

GI02.08.22

From Soft Actuator to Soft Robot Powered with the Oscillating Belousov Zhabotinsky Reaction Baptiste Blanc[1], Ning Zhou[1], Hyunki Kim[3], Eric Y. Liu[2], Ali Aghvami[1], Hyunmin Yi[2], Bing Xu[1], Ryan Hayward[3] and Seth Fraden[1]; [1]Brandeis University, Waltham, Massachusetts, United States; [2]Tufts University, Medford, Massachusetts, United States; [3]UMass Amherst, Amherst, Massachusetts, United States.

Yoshida developed a gel in the late nineties that experiences cyclic swelling and deswelling changes without external stimuli. This self oscillating gel contains a catalyst involved in the Belousov Zhabotinsky (BZ) reaction, an oxydo-reduction cyclic reaction, leading to a cyclic change of solubility of the gel.
Our goal here, is to highlight the engineering principle controlling the mechanical oscillation of the BZ gel and to pave the way to the synthesis of controllable autonomous shape changing hydrogel, which could lead to an autonomous motile hydrogel.
We first present a new synthesis technique, offering high modularity in the gel composition and in its functionalization with the catalyst of the BZ

oscillating reaction.
Thanks to this experimental advance, we optimize the mechanical oscillation of a BZ homogeneous spherical hydrogel, pointing out the critical swelling limitation arising from the minimal size for a BZ gel to chemically oscillate.
We then present a way to "structure" the hydrogel to maximize its mechanical oscillation, and we finally introduce how we are engineering such gels to make them move.

SESSION GI02.09: Materials and Structure
Session Chair: Peer Fischer
Wednesday Morning, November 28, 2018
Hynes, Level 1, Room 111

8:00 AM GI02.09.01
Engineering Reaction–Diffusion Networks with Properties of Neural Tissue for Control of Soft Robots Seth Fraden, Mike Norton and Thomas Litschel; Brandeis University, Waltham, Massachusetts, United States.

Neural tissue evolved 3.5 billion years after the origin of life, which is a testament to its complexity, and is found in almost all multicellular life, which is a testament to its importance. At the coarsest level of description, neurons are non-linear oscillators that when coupled together in tissue through excitatory and inhibitory connections give rise to complex spatio-temporal patterns. When organized, these patterns are capable of processing and storing sensory information, and actuating musculature. Extrapolating from this general definition of a neuronal network as a spatiotemporal pattern generator, we posit these dynamics can be captured on an abiologic reaction–diffusion platform. Here, we report advances in soft lithography that allow the engineering of synthetic reaction–diffusion networks capable of producing a wide variety of spatiotemporal patterns. We employ the well-known oscillatory Belousov–Zhabotinsky reaction and develop methods to create diffusively coupled networks over which we design (i) the topology of the network, the (ii) boundary and (iii) initial conditions, (iv) the volume of each reactor, (v) the coupling strength, and (vi) whether the coupling is of an inhibitory or excitatory nature. It is important to note that the engineering principles we identify are general and can be applied to other oscillatory reaction–diffusion systems. An application for the reaction–diffusion based networks developed here is to the field of soft robotics, where the central pattern generator will serve as the controller of an artificial musculature comprised of chemomechanical gels coupled to the BZ layer.

"Engineering reaction–diffusion networks with properties of neural tissue",
Thomas Litschel, Michael M. Norton, Vardges Tserunyan and Seth Fraden
Lab on a Chip 18, 714 - 722, (2018)
Supplemental files & movies. DOI: 10.1039/c7lc01187c

8:15 AM GI02.09.02
High Power Density, Humidity Driven Actuators for Robotic Applications Onur Cakmak, Xi Chen and Ozgur Sahin; Columbia University, New York, New York, United States.

Humidity responsive materials are versatile alternatives to common actuators in robotics systems, due to ease of actuation with humidity gradients and pervasiveness of water. We have shown that as a humidity responsive material, *Bacillus* spores exhibit high work density actuation [1,2]. To take advantage of micrometer sized spores in macroscopic systems, it is necessary to assemble spores into larger materials without significantly compromising function. The granular nature of spores makes this a challenging task because spores don't adhere well to each other due to small contact areas between adjacent spores, thus making it difficult to transfer mechanical energy. We have shown that combining spores with commercially available UV curable optical and electronic adhesives enable centimeter scale actuators with high work density and specific power. This novel composite is water resistant and retains its function after several liquid water contact. Upon immersion or exposure to humid air from an ultrasonic humidifier, the actuators responded rapidly, in approximately 100 ms which is almost two orders of magnitude better than the response to ambient humidity changes. We estimate that the specific power of spore-based actuators presented here to be between 3.47 and 8.22 kW kg^{-1}. These values are approximately two orders of magnitude higher than mammalian skeletal muscle[3]. The achieved power levels could be sufficient for power demanding applications such as robotic insect flight with a flapping-wing mechanism[4].

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8:30 AM *GI02.09.03
Ultrathin and Light-Weight Organic Solar Cells as the Power Source for Soft Robots Kenjiro Fukuda[1] and Takao Someya[1, 2]; [1]RIKEN, Saitama, Japan; [2]The University of Tokyo, Tokyo, Japan.

Energy harvesting systems are important topic for robotic field because the electrical power is inevitable for most devices to be driven. Among various energy harvesting systems, solar cells are one of the best solution because they can generate milliwatts or higher electric power under the sunshine conditions. Recently we developed ultra-thin organic solar cells which possess high power conversion efficiency (PCE), thermal stability, water-proof property and stretchability simultaneously [1-3]. Our solar cells have ultra-thin properties; the total thickness is only 3 μm and the weight is less than 5 g/m^2, which allows the conformal attachment onto three-dimensional surfaces. In our laboratory, we fabricated such ultra-thin solar cells onto 5 by 5 cm^2 films and generated 36 mW under one-sun illumination (100 mW/cm^2) using the module (total active are is 4.4 cm^2).
In this talk, I will show the detailed performance of our ultra-thin organic solar cells and discuss possibilities for the integration of such power sources with actuators and sensors for the soft robot applications.

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9:00 AM *GI02.09.04
Piezotronics for Next Generation Robotics Zhong Lin Wang[1, 2]; [1]Georgia Institute of Technology, Atlanta, Georgia, United States; [2]Beijing Institute of Nanoenergy and Nanosystems, Beijing, China.

Piezoelectricity, a phenomenon known for centuries, is an effect that is about the production of electrical potential in a substance as the pressure on it changes. For wurtzite structures such as ZnO, GaN, InN and ZnS, due to the polarization of ions in a crystal that has non-central symmetry, a piezoelectric potential *(piezopotential)* is created in the crystal by applying a stress. The effect of piezopotential to the transport behavior of charge carriers is significant due to their multiple functionalities of piezoelectricity, semiconductor and photon excitation. By utilizing the advantages offered by these properties, a few new fields have been created. Electronics fabricated by using inner-crystal piezopotential as a "gate" voltage to tune/control the charge transport behavior is named *piezotronics,* with applications in strain/force/pressure triggered/controlled electronic devices, sensors and logic units. This effect was also extended to 2D materials such as MoS_2. The objective of this talk is to introduce the fundamentals of piezotronics and their application for robotics and human-machine interfacing.
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9:30 AM GI02.09.05
Metallic Nanowires—Fabrication, Microstructure and Properties Wenting Huang and Gunther Richter; Max Planck Institute Intelligent Systems, Stuttgart, Germany.

Building nanodevices for applications leads to a myriad of challenges on materials and assembly level. Still nanosized objects have the prospect to be building blocks for future complex smart, autonomous or intelligent systems. A challenge for bringing macroscopic building designs and concepts into the nanoworld, that decreasing dimensions lead to changing physical properties and behaviors. Especially systems below 100 nm and above the size of single molecules exhibit peculiar properties. Surfaces, interfaces, grain boundaries, dislocations that influence the behavior of macroscopic devices will dominate the performance of those below 1 µm. Therefore, to stay relevant and open new research areas by breaking through old limits, the interlinkage of microstructure, fabrication and capacity of devices have to be newly addressed in the same length scale.
We present the fabrication of metallic nanostructures by physical vapor deposition and will briefly discuss the influences of diffusion on the microstructure formation. Examples from 2D-thin film, island, perlocated structures and one-dimensional nanowires will act as illustration.
The changing physical properties, mechanical, electrical and magnetic, are demonstrated by investigations of metallic nanowires. Due to the absence of internal defects, such as dislocations or grain boundaries, tensile strengths close to the predicted theoretical strength are observed. Cu exhibits a tensile strength of ~6 GPa, Au of ~1 GPa. The deformation is carried by partial dislocation nucleation and propagation and consequently by twin formation. Since no defects act as scattering center, the conductivity does not increase with decreasing diameter of the nanowires, but remains close to the perfect bulk values. No size effect is observed but a constant conductivity. The magnetic domain structure was studied by electron holography. Only one single domain is present in ferromagnetic metallic nanowires.
In conclusion we show how microstructural tailoring leads to changing physical properties and therefore to improved performances in nanosystems. In the long term, this might open the path to new research avenues and reintroduce seemingly old materials systems in novel design concept for nanodevices.

9:45 AM GI02.09.06
Dynamically Tunable Dry Adhesion via Sub-Surface Stiffness Modulation Milad Tatari[1], Amir Mohammadi Nasab[1], Kevin T. Turner[2] and Wanliang Shan[1]; [1]University of Nevada Reno, Reno, Nevada, United States; [2]University of Pennsylvania, Philadelphia, Pennsylvania, United States.

Tunable dry adhesion has a range of applications, including transfer printing, climbing robots, and gripping in automated manufacturing processes. Here, a novel concept to achieve dynamically tunable dry adhesion via modulation of the stiffness of sub-surface mechanical elements is introduced and demonstrated. A composite post structure, consisting of an elastomer shell and a core with a stiffness that can be tuned via application of electrical voltage, was fabricated. In the non-activated state, the core is stiff and the effective adhesion strength between the composite post and contact surface is high. Activation of the core via application of electrical voltage reduces the stiffness of the core, resulting in a change in the stress distribution and driving force for delamination at the interface and a reduction in the effective adhesion strength. The adhesion of composite posts with a range of dimensions were characterized and activation of the core was shown to reduce the adhesion by as much as a factor of six. The experimentally observed reduction in adhesion is primarily due to the change in stiffness of the core. However, the activation of the core also results in heating of the interface and this plays a secondary role in the adhesion change.

10:00 AM BREAK

SESSION GI02.10: Small Robots I
Session Chair: Bradley Nelson
Wednesday Morning, November 28, 2018
Hynes, Level 1, Room 111

10:30 AM *GI02.10.01

Shape-Programmable Magnetic Soft-Bodied Millirobots Metin Sitti; Max Planck Institute for Intelligent Systems, Stuttgart, Germany.

Soft functional active materials could enable physical intelligence for small-scale (from a few millimeters down to a few micrometers overall size) devices and robots by providing them unique capabilities, such as shape changing and programming, physical adaptation, and multi-functional and drastically diverse dynamics. In this talk, our recent activities on design, manufacturing, and control of new shape-programmable active soft matter and untethered soft robots at the milli/microscale are reported. First, a computational design and fabrication method is introduced to create 2D shape-programmable magnetic soft elastomers that can generate desired large number of shapes using a programmed non-homogeneous magnetization profile and uniform magnetic field control input. Such magnetic shape change/actuation can happen very fast and wirelessly, which are significant advantages. Next, using such methodology, a grand challenge in small-scale mobile robotics is addressed: how to navigate mobile robots in complex environments with multiple terrains (e.g., on solid surfaces, inside fluids, at the fluid-air interfaces) using multiple locomotion modalities like animals in nature? Using programmed dynamic deformations of the robot's soft elastomeric body and body torques, such soft-bodied robot is demonstrated to be able to have seven locomotion modalities (undulatory swimming, jellyfish-like swimming, water meniscus climbing, jumping, ground walking, rolling, and crawling inside constrained environments) to be able to navigate on complex environments, such as inside the human body. Moreover, dynamic shape control is used to actively transport and deliver cargos integrated to the robot's body. Preliminary ultrasound-guided navigation of such soft robots is presented inside an *ex vivo* chicken tissue towards their medical applications to deliver drugs and genes locally and heat the local tissues for hyperthermia and cauterization.

11:00 AM GI02.10.02
Multimodal Control of Magnetic Millibot for Programmable Collective Rotation Hajun Lee, Jeeyoon Yi, Hyeonseo Song, Junkyu Choe and Jiyun Kim; Mechanical Science and Engineering, Ulsan National Institute of Science and Technology, Ulsan, Korea (the Republic of).

Creating individual and collective motions in material based distributed systems, e.g. active matter and self-assembling particles, pose challenges in the design of both physical components and control algorithms that can operate at desired scales. Among them, meso-scale floating magnetic components rotating at liquid-air or liquid-liquid interface have been widely engineered to create patterns balancing magnetic rotation and corresponding hydrodynamic interactions, attributing their potentials to remote actuation and easy fabrication. Most of those systems, however, are only composed of identical components, lowering the diversity and the complexity in programming their spatiotemporal collective behaviors.
Here, we develop millimeter-scale polymer based magnetic structures, named as 'millibot', and map their multi-modal rotational behaviors in a chosen magnetic field intensity and frequency range. Millibots have identical rectangular shapes but diverse magnetic properties, making them have different map in their rotational behaviors. Using these actuation maps, we are able to selectively control the collective rotation of heterogeneous milibot groups or sub-groups in a programmable manner.
To achieve this, we developed three types of millibots with different magnetic properties; a millibot can have the magnetic anisotropy with self-assembled magnetic chains, randomly dispersed magnetic particles with several concentrations, or the mixture of ferromagnetic and superparamagnetic particles. To embed magnetic properties in the millibots, magnetic particles were dispersed in the photocurable polymer, PEGDA diluted with DI water, and shaped via photopolymerization. 2-axis magnetic field generator, whose magnetic field ranges in intensity from 100 to 800 Oe and in frequency from 0 to 4 Hz, was used to drive the rotations in millibots and consequently, we mapped the multimodal rotations of each type of millibot.
We observed shift, shrinkage or expansion of individual rotation mode ranges according to the type of millibots. This allows us to choose and program the collective rotation of entire millibot group or chosen sub-group. To show this capability, we demonstrated that four different millibots exhibiting different rotational behaviors under the certain condition were switched their behavior to identical collective rotation in another condition. Also, fifteen millibots which is composed of three sub-groups were controlled to show diverse collective rotations of sub-groups.
As a result, embedding diverse material properties in the physical components of distributed systems provide an advanced way of designing and controlling the collective behaviors of heterogeneous distributed system in a programmable manner. We expect that this approach will enhance the behavioral capability of meso-scale particle collectives for diverse applications including programmable matter, robotics, bio-medical systems and so on.

11:15 AM GI02.10.03
X-Ray Driven Microswimmers Zhaoyi Xu and Ji Tae Kim; Department of Mechanical Engineering, The University of Hong Kong, Hong Kong, Hong Kong.

Light-powered manipulation of small objects in fluids significantly affects fields as diverse as drug/cell delivery, microsurgery, environmental remediation, and self-assembly/nanofabrication. Although many clever techniques based on UV-visible-NIR light have been devised, new methods that can have sufficient penetrating power into biological bodies are still in great demand. Since discovered by Röntgen, X-rays have long been regarded as the most celebrated light-source for non-invasive, whole-body medical imaging because of its outstanding penetration.
Here, we observed that X-rays can drive propulsive motion of a half-metal coated Janus microparticle in aqueous environment. Using a full-field transmission X-ray microscope (TXM) with synchrotron hard X-rays, we simultaneously triggered and visualized the propulsive motion at single-particle level. Our real-time observation at nanoscale revealed that the motion follows bubble growth induced by radiolysis of water at the metal/water interface under X-ray irradiation. This study opens a potential to operate micro/nanorobots under whole-body medical imaging. In this talk, we will present our results and discuss the prospects of our work for potential applications in medicine.

11:30 AM GI02.10.04
Visible-Light-Gated Reconfigurable Rotary Actuation of Electric Nanomotors Zexi Liang[1] and Donglei (Emma) Fan[1, 2]; [1]Materials Science and Engineering, The University of Texas at Austin, Austin, Texas, United States; [2]Mechanical Engineering, The University of Texas at Austin, Austin, Texas, United States.

Highly efficient and widely applicable working mechanisms that allow nanomaterials and devices to respond to external stimuli with controlled mechanical motions could make far-reaching impact to reconfigurable, adaptive, and robotic nanodevices. Here, we report an innovative mechanism that allows multifold reconfiguration of mechanical rotation of semiconductor nanoentities in electric (E) fields by visible light stimulation. When illuminated by light in the visible to infrared range, the rotation speed of semiconductor Si nanowires in electric fields can instantly increase, decrease, and even reverse the orientation depending on the intensity of the applied light and the AC E-field frequency. This multifold rotation configuration is highly efficient, instant, and facile. Switching between different modes can be simply controlled by the light intensity at an AC frequency. Experimentations, theoretical analysis, and simulations are carried out to understand the underlying principle, which can be attributed to the optically tunable polarization of Si nanowires in aqueous suspension and an external electric field. Finally, leveraging this newly discovered effect, we successfully differentiate semiconductor and metallic nanoentities in a non-contact and non-destructive manner. This research could inspire a new class of reconfigurable nanoelectromechanical and nanorobotic devices for optical sensing, communication, molecule release, detection, nanoparticle separation, and microfluidic automation.

11:45 AM GI02.10.05
Materials for Actuation and Testing of Miniaturized Robots Eunjin Choi[1], Fabian Adams[2], Kai Melde[1], Stefano Palagi[1], Tian Qiu[1] and Peer Fischer[1, 3]; [1]Max Planck Institute for Intelligent Systems, Stuttgart, Germany; [2]Department of Urology, University Medical Center Freiburg, Freiburg,

Germany; [3]Institute for Physical Chemistry, University of Stuttgart, Stuttgart, Germany.

Miniaturization is critical for many robotic devices, especially in the field of medical robotics. Numerous small-scale robots have been developed for potential medical applications, such as targeted drug delivery[1], minimally invasive surgery[2], measurement of biological fluids[3], and endoscopic imaging[4]. An essential component of these robots are the miniaturized actuators, which need to be small in size, powerful in the actuation force, safe for the interaction with biological tissues, and ideally untethered for more dexterity of the robots. Traditional electronics based systems are often stiff and if multiple wires are used, they are too bulky for instance for minimally invasive applications. The development of new materials is essential to enable new compact actuators and to simplify robot design.

Here, we present a surface actuator – essentially a thin film – that needs no electrical or light input and that is based on functional material interfaces. The interface consists a two-dimensional array of micro-bubbles that can be resonantly excited by ultrasound. The microfabricated thin film causes strong acoustic streaming, when it is wirelessly excited by the low-frequency ultrasound[5]. This smart surface permits unique addressability and thus enables many degree of freedom actuation of multiple actuators. Although the surface actuator is only hundreds-of-micron in thickness, it is powerful enough to remotely actuate a centimeter-scale robot in water and a miniaturized endoscope for urinary tract video-imaging.

In order to test miniaturized devices, such as our ultrasound-activated acoustic streaming devices and to evaluate their performances, we also developed high-fidelity organ phantoms using soft materials and 3D fabrication methods. The phantoms are based on high accuracy CAD models and the soft materials are engineered to mimic real biological tissues with similar mechanical, haptic, and visual properties under endoscopy or common medical imaging techniques, e.g. CT and ultrasound. We will present examples of smart organ phantoms, such as the urinary tract with kidney phantom that allowed the development of our miniaturized medical devices. The phantoms possess a detailed anatomical structure for testing and training of endoscopes[6]. A prostate phantom even allows the surgeon to perform electrocautery surgery and to quantitatively evaluate the surgical performance. The phantoms are expected to be important in development of surgical robots.

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SESSION GI02.11: Small Robots II
Session Chairs: Donglei (Emma) Fan and Peer Fischer
Wednesday Afternoon, November 28, 2018
Hynes, Level 1, Room 111

1:30 PM *GI02.11.01

Magnetic Colloidal Microswarm for Targeted Delivery Jiangfan Yu[1] and Li Zhang[1, 2, 3]; [1]Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong, China; [2]Chow Yuk Ho Technology Centre for Innovative Medicine, The Chinese University of Hong Kong, Hong Kong, China; [3]CUHK T-Stone Robotics Institute, The Chinese University of Hong Kong, Hong Kong, China.

In nature, various types of swarm behaviors occur, such as a flock of birds and a swarm of ants, which stem from local communications of limited individuals. Through collective pattern formation and reconfiguration, these animals dramatically change their swarming patterns according to the environment they interact with. To date, some large-scale robotic systems can well mimic the complex swarm behaviors of natural creatures through algorithm design and wireless communication [1]. However, due to the absence of onboard processers, sensors and actuators, to create a robotic system with functional swarm behaviors at the small scales remains challenging. Herein, we report paramagnetic nanoparticles as building blocks to investigate collective behavior of microrobotic swarm in fluid.

Recently, we found a novel method to disassemble paramagnetic nanoparticle chains using a programmed dynamic magnetic field [2]. Thousands or even millions of colloidal agents can be disassembled and spread simultaneously due to hydrodynamic drags and magnetic dipole-dipole repulsive interactions, respectively. As the reversed process, we also presented that the spread colloids can be assembled into vortex-like paramagnetic nanoparticle swarms (VPNS) using a rotating magnetic field [3]. The VPNS exhibits a dynamic-equilibrium structure, in which the nanoparticles perform synchronized motions. Moreover, by tuning the applied magnetic fields, the VPNS was capable of performing multimodal pattern reconfiguration, and we also investigated the reversible merging and splitting of the vortex-like swarms/sub-swarm. We demonstrated that the VPNS is able to pass through curved and branched fluidic channels with high swimming velocity, positioning precision and access rates (over 90%) to a target. Localized energy delivery with tunable and enhanced hyperthermia heating effect was demonstrated as well [4]. In addition, we have discovered a new strategy to reconfigure the paramagnetic nanoparticles into ribbon-like microswarms, which are capable of performing reversible elongation with an extremely high aspect ratio of the dynamic pattern. Our work thus sheds light on the fundamental understanding and control of magnetic microrobotic swarms.

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2:00 PM *GI02.11.02
Designing Self-Powered Nano and Microbots Ayusman Sen; The Pennsylvania State University, University Park, Pennsylvania, United States.

Self-powered nano and microscale moving systems are currently the subject of intense interest due in part to their potential applications in nanomachinery, nanoscale assembly, robotics, fluidics, and chemical/biochemical sensing. One of the more interesting recent discoveries has been the ability to design nano/microparticles, including molecules, which catalytically harness the chemical energy in their environment to move autonomously. These "bots" can be directed by chemical and light gradients. Further, our group has developed systems in which chemical secretions from the translating micro/nanomotors initiate long-range, collective interactions among the particles. This behavior is reminiscent of quorum sensing organisms that swarm in response to a minimum threshold concentration of a signaling chemical. In addition, an object that moves by generating a continuous surface force in a fluid can, in principle, be used to pump the fluid by the same catalytic mechanism. Thus, by immobilizing the nano/micromotors, we have developed nano/microfluidic pumps that transduce energy catalytically. These non-mechanical pumps provide precise control over flow rate without the aid of an external power source and are capable of turning on in response to specific analytes in solution. In addition, the catalytic pumps can be harnessed for directional delivery of microparticles in specific locations in space.

2:30 PM *GI02.11.03
Ingestible Self-Propelled Microrobots—Toward *In Vivo* Use Wei Gao; Engineering and Applied Science, California Institute of Technology, Pasadena, California, United States.

While synthetic micromotors have been evaluated extensively under in vitro conditions for over a decade, their in vivo function has rarely been explored. Zn and Mg based micromotors, powered by body fluids, have shown unique advantages to operate at different regions of the gastrointestinal tract. In this talk, I will highlight several examples of recent in vivo investigations based on these biocompatible and biodegradable biofluids powered microrobots, including precise micromotor tissue localization and retention, in vivo imaging, and enhanced drug delivery. I will also cover some early in vitro studies that paved the way for the current in vivo applications. These works open the door to a number of in vivo and clinical applications of these synthetic motors.

3:00 PM BREAK

4:00 PM GI02.11.04
Engineering Hybrid Machines—From Nanobots to 3D BioBots Samuel Sanchez; Smart Nano Bio Devices, Institute for Bioengineering of Catalonia/ICREA, Barcelona, Spain.

The combination of biological components and artificial ones emerges into what we called hybrid machines or robots. Hybrid nano-bots have the ability to convert bio-available fuels to generate propulsion force to swim. They may be eventually used in vivo for transporting drugs to target locations in a controlled manner. Additionally, their active propulsion and multifunctionality of the different components of the nanoarchitecture makes them useful in sensing and cleaning water where they swim. However, before that, fundamental understanding on motion mechanism, materials considerations, in vitro assessment of drug delivery, toxicity, and their shape and size dependence on those parameters is needed.
Hybrid nano- and micro-robots combine nanomaterials with enzymes and with motile cells efficient delivery, sensing, imaging and biofilm penetration. On a larger scale, we use 3D bioprinting techniques to fabricate cm-scaled hybrid BioRobots based on the combination of hydrogels and cells that contract in synchrony upon external stimuli, and exercise training, alike artificial muscles.

4:15 PM GI02.11.05
Molecular Direct-Driven Untethered Macro Soft Robots in Liquid—Design, Maneuver and Application Demonstration Zhigang Wu, Liangxiong Lv, Fen Li, Pan Deng and Kang Wu; Huazhong University of Science & Technology, Wuhan, China.

By extracting the kinetic energy in the molecular cooperation of an active material and its ambient liquid environment, this work reports a new strategy to design and maneuver untethered soft robots in liquid. This strategy gets rid of those tethered pipes/wires which are commonly used for energy transport in current soft robots, without robot design re-designing or changing body materials for the introducing new active materials. Using this newly developed strategy, we demonstrate a world first, molecular directly driven, macro soft robot in a liquid, and a soft robot swarm. This approach may provide a new possibility to design, fabricate and control autonomous robotics in liquid.
Untethered soft robotics inspired from nature with new design, fabrication and control strategies have been totally changing our cognition of robotics. However, the characteristics of power source forms cannot break through the inherently limitation of thermal/mechanical performance of soft materials. Here, we presented a novel approach through contacting kinds of molecules such as amphiphilic ones with liquids. During the process, the introduced molecules interact with the ambient liquid and lead to a non-equilibrium state, resulting in a higher energy state of Gibbs free energy. Consequently, this energy gap results in a collective molecular movement that can be observed in macro scale due to molecular re-organization in micro scale e.g., oil drops spreading on water. When the molecules of such material leave their initial attached surface on the robot during their molecular re-organization process, a well-directed opposite impulse to their initial attached surface is generated according to the principle of momentum conservation. The movement of soft robots depends on the kinetic energy through a molecular interaction with the external environment without any high energized process or tethered pipes. Further, by deploying materials spatially on the attached robots, the trajectory control can be obtained such as straight going and turning in liquid for single robots.
To imitate maneuvering such a robot in practical scenarios, a back dyed robot passed through precisely a toy rockery tunnel following the designed path with an optical detector, and triggered the lighting color change of an LED indicator. Without introducing any mechanical movement components, our approach has a near zero-noise level during the running process. Furthermore, by carefully aligning 32 robots towards a burning flame on an open water surface, we demonstrated a robot swarm that can be highly-centered to the same spot simultaneously to assure a hit on the given target as accurately as possible (here to extinguish the flame).

4:30 PM GI02.11.06
Mechanical Acceleration of DNA Capture and Detection by Robotizing Bio-Photonic-Plasmonic Microsensors Jianhe Guo[1] and Donglei (Emma) Fan[1, 2]; [1]Materials Science and Engineering, The University of Texas at Austin, Austin, Texas, United States; [2]Department of Mechanical Engineering, The University of Texas at Austin, Austin, Texas, United States.

Efficient capture of deoxyribonucleic acid (DNA) on solid surfaces has received immerse research interest for various biotechniques, including DNA extraction, preconcentration, detection, and separation. This work reports an original mechanism to actively accelerate the DNA capture process and significantly reduce the detection time by mechanically rotating bio-photonic-plasmonic hybrid microsensors. The photonic-plasmonic microsensors consist of diatom frustules with surface-coated magnetic thin films and uniformly distributed plasmonic silver (Ag) nanoparticles. The diatom frustules are made of silica with ordered arrays of nanopores offering large surface-to-volume ratio and synergistic-plasmonic resonance for the capture and detection of DNA with surface enhanced Raman spectroscopy (SERS). By manipulating with magnetic tweezers, the photonic-plasmonic microsensors transport and self-assemble in microwells and microfluidic channels, and rotate with tunable speeds for the capture and detection of DNA molecules. Experiments show the capturing rate of DNA can be significantly enhanced by at least 4 times by controlling the rotation speed of the microsensor to 1200 rpm. At a concentration as low as 80 nM/ml, Raman signals of DNA is obtained 3-time faster than those without rotation. The fundamental mechanism is investigated and attributed to the fluidic boundary layer effect, where the Nernst diffusion layer on the surface of the robotized microsensors is monotonically reduced with flow speed.

4:45 PM GI02.11.07
Micromotor-Enabled Active Drug Delivery to Treat Gastrointestinal Diseases Jinxing Li, Pavimol Angsantikul, Berta Esteban, Liangfang Zhang, Joseph Wang and Fernando Soto Alvarez; NanoEngineering, University of California, San Diego, La Jolla, California, United States.

Advances in bioinspired design principles and nanomaterials have led to tremendous progress in autonomously moving synthetic nano/micromotors with diverse functionalities in different environments. However, a significant gap remains in moving nano/micromotors from test tubes to living organisms for treating diseases with high efficacy. Here we present the first, to our knowledge, in vivo therapeutic micromotors application for active drug delivery to treat gastric bacterial infection in a mouse model using clarithromycin as a model antibiotic and *Helicobacter pylori* infection as a model disease. The propulsion of drug-loaded magnesium micromotors in gastric media enables effective antibiotic delivery, leading to significant bacteria burden reduction in the mouse stomach compared with passive drug carriers, with no apparent toxicity. Moreover, while the drug-loaded micromotors reach similar therapeutic efficacy as the positive control of free drug plus proton pump inhibitor, the micromotors can function without proton pump inhibitors because of their built-in proton depletion function associated with their locomotion.