Institute for Soldier Nanotechnologies

Founded in 2002, the Institute for Soldier Nanotechnologies (ISN) is a US Army University-Affiliated Research Center (UARC), designed as a three-member team intended to leverage the unique capabilities of the US Army, industry, and MIT. Its mission is to help the Army and other US military services develop innovative capabilities for soldiers and other warfighters through basic research in nanotechnology, and by transitioning promising outcomes of that research. This mission includes decreasing the weight that soldiers and other warfighters carry, improving blast and ballistic protection, creating new methods of detecting and detoxifying chemical and biological threats, and providing physiological monitoring and medical treatment.

Funding for ISN basic research was more than $150 million over its first 15 years, with the majority of these funds dispensed through a series of independent, five-year contracts, including ISN-1, ISN-2, and ISN-3, administered by the US Army Research Laboratory-Army Research Office (ARL-ARO). Nearly $20 million in additional funds were provided by the Army to facilitate the transitioning of promising outcomes of ISN research to the next stages of development, with the bulk of these funds distributed to ISN partner companies and Army Science and Technology (S&T) installations. There was also substantial co-investment in ISN basic research by industry partners and MIT.

Following a series of reviews by the Army, the ISN was renewed for the third time in 2017. The ISN-4 research portfolio went into effect on January 1, 2018. ISN-4 brought significant structural changes to the ISN, including its financial administration. Unlike with previous renewals, when a single new contract was issued, ISN-4 has two core funding instruments. The indefinite delivery/indefinite quantity (IDIQ) procurement contract for ISN-3, which sustains the ISN as a UARC, was extended for five years through 2022 in order to continue to fund the ISN headquarters, management, laboratories, and facilities at 500 Technology Square (Building NE47), and to be able to accept additional customer funding from the Army and the broader US Department of Defense for projects that are not part of the core ISN-4 portfolio. Additionally, a new, separate Cooperative Agreement (CA) was established to fund research projects that make up the core ISN-4 research portfolio. The aim of the CA is to simplify Army administrative procedures, enabling Army scientists to visit MIT for collaborative work with ISN researchers. The total amount of funding from ARL-ARO for ISN-4 core work is expected to be approximately $27.5 million, or approximately $5.5 million per year. The ISN continues to seek additional sources of funding to strengthen its portfolio and expand its contributions to soldier and warfighter capabilities.

Thirty-five faculty members and research scientists representing more than a dozen MIT academic departments, labs, and centers, as well as nearly 75 graduate students and postdoctoral associates, participate in ISN research. ISN research typically results in more than 100 refereed publications annually, including in distinguished scientific journals such as *Science, Nature, Advanced Materials, Physical Review Letters,* and the *Proceedings of the National Academy of Sciences*. Additionally, more than 350 people visit ISN each year for briefings on research endeavors and tours of ISN facilities. Of particular note, the Honorable Bruce Jette, PhD, assistant secretary of the Army for acquisition, logistics, and technology, visited the ISN in May 2018, and Michael Kratsios, deputy assistant to the President and deputy US chief technology officer, visited in June 2018.

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Research Portfolio

The ISN's signature interdisciplinary research agenda has evolved over the course of its first fifteen years into a focused program reflecting the areas in which the ISN and the Army see the potential for especially strong soldier impacts. For ISN-4, this structure has been further updated and redefined to better align with and more efficiently respond to guidance from the Army, while also working within the constraints of Army budget reductions. Team-based innovation is a hallmark of the ISN's intellectual course, with new ideas and collaborations emerging frequently. The ISN research portfolio is currently divided into three Strategic Research Areas that are further divided into specific projects.

Strategic Area 1: Soldier Protection, Battlefield Care, and Sensing

Project 1.1 Advanced Multiscale Methods for Modeling of Fracture in Novel Nanomaterials
Principal Investigators (PIs): Raúl Radovitzky (Aeronautics and Astronautics), Keith Nelson (Chemistry), and Xuanhe Zhao (Mechanical Engineering [MechE], Civil and Environmental Engineering)

Project 1.2 Shock Mitigating and Reinforcing Molecular Nanocomposites
PI: Michael Strano (Chemical Engineering [ChemE])

Project 1.3 Design & Testing of Polymers for Improved Soldier Protection
PIs: Keith Nelson (Chemistry), Tim Swager (Chemistry), Greg Rutledge (ChemE)

Project 1.4 Superelastic Granular Materials for Impact Absorption
PIs: Chris Schuh (Materials Science and Engineering [DMSE]), Raúl Radovitzky (Aeronautics and Astronautics), Kenneth Kamrin (MechE)

Project 1.5 Rapid Hemostasis for the Treatment of Incompressible Wounds
PIs: Bradley Olsen (ChemE), Paula Hammond (ChemE), Shuguang Zhang (Media Lab, Center for Bits and Atoms)

Project 1.6 Empowering Future Vaccines & Immunotherapies with Nanotech-based Adjuvants
PI: Darrell Irvine (DMSE, Biological Engineering)

Strategic Area 2: Augmenting Situational Awareness

Project 2.1 Uncovering Chemical Stability & Charge Transfer Mechanisms at Electrode-Electrolyte Interfaces of Li-ion Batteries
PI: Bilge Yildiz (Nuclear Science and Engineering, DMSE)

Project 2.2 Mid- & LW-Infrared Detector Arrays on Flexible Substrates
PIs: Tomás Palacios (Electrical Engineering and Computer Science [EECS]), Dirk Englund (EECS), Jing Kong (EECS)

Project 2.3 Room Temp LWIR-THz Detection via E-field Enhancement-Induced QD Upconversion
PIs: Moungi Bawendi (Chemistry), Vladimir Bulovic (EECS), Keith Nelson (Chemistry), Adam Willard (Chemistry)

Project 2.4 Particulate Fluid Fiber Processing for Fabric Communications
PIs: Yoel Fink (DMSE, EECS), John Joannopoulos (Physics), Alexander Stolyarov (MIT Lincoln Laboratory)

Project 2.5 Nano-plasmonics for Soldier Applications
PIs: Marin Soljačić (Physics), Jing Kong (EECS), Steven Johnson (Mathematics)

Strategic Area 3: Transformational Nano-optoelectronic Soldier Capabilities

Project 3.1 Solid State Power Generation at Millimeter Scales
PIs: Ivan Celanovic (ISN), Marin Soljačić (Physics), Peter Fisher (Physics)

Project 3.2 Photonic Integrated Circuits for Lidars, Displays & Low-Power Computing
PIs: Dirk Englund (EECS), Marin Soljačić (Physics)

Project 3.3 Nanophotonics-Enhanced Systems for the Soldier
PIs: Steven Johnson (Mathematics), Marin Soljačić (Physics), John Joannopoulos (Physics)

Project 3.4 Applications of Novel Topological Phenomena
PIs: Liang Fu (Physics), Nuh Gedik (Physics), Marin Soljačić (Physics)

Project 3.5 Novel Multimaterial Inks for Multiscale 3D Device Printing
PIs: Yoel Fink (DMSE, EECS), Alexander Stolyarov (MIT Lincoln Laboratory)

Transitioning

The ISN places a strong emphasis on basic research—however, transitioning promising outcomes of that research, or technology transfer, is also a crucial component of the ISN mission. To this end, the ISN works with the Army, industry partners, startups and other companies, and the MIT Technology Licensing Office to help assure that promising ISN innovations leave the lab and benefit soldiers, other warfighters, and first responders as rapidly and efficiently as possible. The ISN is pleased to count John R. McConville, an ARL-ARO Technology Transfer Officer (TTO), among our full-time team at headquarters. It is the TTO's charge to help maximize the effectiveness and efficiency with which ISN technologies progress from the laboratory bench to more advanced stages of development.

Throughout its history, the ISN has been the source of several highly important technology transitions. One very notable transition is the Advanced Functional Fabrics of America (AFFOA) Manufacturing Innovation Institute. Founded in 2016 by the US Department of Defense and led by MIT as a part of the National Network for Manufacturing Innovation (NNMI), AFFOA is based on foundational ISN research led by ISN-affiliated MIT faculty member Professor Yoel Fink. In June 2017, AFFOA unveiled its dedicated facilities, located a short walk from the main MIT campus, along with a sampling of prototypes containing advanced optoelectronic fiber devices.

Sampling of ISN Research Accomplishments

Unique ISN Experimental Setup May Lead to Better Armor Materials

A team comprising ISN-affiliated Haslam and Dewey Professor of Chemistry Keith Nelson, staff scientist David Veysset, ISN Principal Research Scientist Steve Kooi, and ARL scientist Alex Hsieh, who is stationed at the ISN, has used a unique experimental setup to discover that poly(urethane urea) elastomers (PUUs) exhibit hyperelastic properties upon very fast impact of solid particles. The setup, which used a laser to accelerate tiny silica particles at the PUUs and allows for the entire process to be imaged as it occurs, showed that the material under examination not only stiffened substantially on impact but also rebounded afterward. Previously, such a response had not been seen in bulk elastomers, and the existence of hyperelastic behavior here could lead to new material design processes and, ultimately, more robust protective materials for soldiers and other warfighters, first responders, and, potentially, civilian applications. This experiment has been detailed in an article published in the journal *Polymer*.

Enhancing Light-Matter Interactions

As detailed in a paper in the journal *Nature Photonics*, a team led by John Joannopoulos, ISN director and Francis Wright Davis Professor of Physics, and Marin Soljačić, professor of physics, has theoretically devised a new means to increase light-matter interactions. A problematic limitation to the way light and matter relate is that at a given energy level the momentum of electrons in matter is vastly higher than that of light particles (photons), which causes very weak interplay. Most attempts to rectify this issue have been by manipulating the matter side of the interaction. The new approach instead proposes shrinking the wavelength of light, thereby increasing the momentum of the photons so that it more closely matches that of the electrons. Although the work is both theoretical and in its initial stages, if fully realized, it could result in the development of advanced lasers and light-emitting diodes, as well as solar cells that are able to absorb light from a broader swath of the spectrum.

Short-Wave Infrared Biomedical Imaging

Biological imaging in the short-wave infrared (SWIR) regime of 1000-2000nm wavelengths has substantial benefits over common imaging in the near infrared (NIR, 700-900nm wavelengths). It can provide vastly clearer images that allow for better visualization of blood flow through tiny capillaries, capture metabolic processes in action, and make discernible biological activity at the molecular level. However, contrast agents for SWIR imaging have yet to be approved for clinical use with human patients. A study led by Moungi Bawendi, the Lester Wolfe Professor of Chemistry and an ISN PI, and published in the *Proceedings of the National Academy of Sciences*, has shown that a fluorescent dye first approved for human clinical use in the late 1950s and commonly employed for NIR imaging provides remarkable contrast in SWIR imaging, as well. In fact, the dye, indocyanine green (ICG), is the best SWIR contrast agent known, outperforming purpose-built dyes currently in use for pre-clinical purposes. The research team is now investigating the reasons for ICG's impressive fluorescence in hopes of ultimately improving upon it.

Exotic Topological Phenomena in Open Systems

While topological phenomena have been of great and increasing interest to the physics community, examination of these effects has been relegated mostly to those present in closed systems—systems in which neither energy nor matter may enter or leave. Analyzing open systems has proved problematic due to the potential variability of energy levels or quantity of matter. Now, drawing upon advancements made in 2016 that allow for the direct visualization of the energy contours in a system, a team led by ISN-affiliated MIT professors Marin Soljačić, Liang Fu, Keith Nelson, and John Joannopoulos was able to discover two different phenomena in open systems that they have detailed in the journal *Science*. First, the team found for the first time a Fermi arc in the bulk of the material rather than on its surface. Connecting two "exceptional points," these arcs defied the expectation that energy contours are always closed loops. Second, the researchers discovered a field of light in which the polarization twisted like a Möbius strip corresponding to the direction of its emission. Although both of these phenomena, and the means by which they were observed, are currently of more scientific and academic interest than practical, they could lead to entirely new fields of study in physics and potential, eventual application in optical computing, data transmission, and lasers.

3D-Printed Soft, Magnetically-Actuated Devices

As detailed in an article in *Nature*, ISN-affiliated MIT professor Xuanhe Zhao has succeeded in printing a three-dimensional, soft device that can be actuated magnetically, obviating the need for the tethers or external pumps of water- and air-driven devices while responding much more rapidly than systems based on, for example, hydrogels or liquid crystal elastomers. These are not the first magnetically actuated robots, but other devices have been produced by a molding process that relegates them to very simple movements and architectures. Zhao's 3D-printing process allows for more complex movements due to the potential for zones of different magnetic alignment. Zhao foresees possible use in a variety of biomedical applications.

Ultrastrong, Ultrafine Electrospun Fibers

The ISN-affiliated Lammot du Pont Professor of Chemical Engineering, Gregory Rutledge, working with postdoctoral associate Jay Park, currently an Oak Ridge Institute for Science and Education (ORISE) postgraduate fellow at ARL, has developed a new gel electrospinning process enabling the creation of ultrastrong and tough fibers with nanoscale diameters. Described in an article in the *Journal of Materials Science*, the resulting fibers meet or exceed the properties of commercially available materials such as Kevlar®, Spectra®, and Dyneema®, and have strengths similar to carbon and ceramic fibers but much higher toughness and much lower weight. Eventual applications in advanced armors are predicted, as the new materials could be used to fashion protective ensembles that combine the same standard of ballistic defense with decreased bulk.

AI-enabled Nanoparticle Design

A team including Professor Marin Soljačić and Professor John Joannopoulos of MIT, and Dr. Brendan DeLacy of the US Army's Edgewood Chemical/Biological Center has developed an AI-enabled tool for the design of specialized nanoparticles. As detailed in an article in the journal *Science Advances*, by entering information on a large number of exemplar particles, the process "teaches" a computational neural network how differences in particle composition and structure affect the particle's behavior. Once the neural network has learned enough, the process can be reversed: the desired behaviors are entered into the system, which then responds with the necessary particle structure and composition. Practical applications of the technique are not limited to the actual design of nanoparticles, which could result in advanced obscurants and imaging devices, but could also help scientists streamline and accelerate their research procedures by minimizing the need for full, time-intensive, computationally expensive simulations.

Advances in the Understanding of Sprayed Metal Coating

Two recent publications—one in *Physical Review Letters* and the other in *Scripta Materialia*—have resulted from ISN-funded collaborative research by MIT faculty members Keith Nelson and Christopher Schuh that images for the first time the impact-generated melting of sprayed metal particles on a surface. It has long been supposed that the tiny metal particles in a sprayed coating melt upon impact with a metal surface but, due to its incredible speed, it has never before been possible to witness that process as it happens. Thanks to a camera designed by then-postdoc David Veysset (now a staff scientist) that can record an image in just three nanoseconds, the research team was able to do just that. In a result that seems somewhat counterintuitive, the team found that the melt often hindered the adhesion process, as the liquified particle would splash off the surface. This understanding, and the tool used to acquire it, could help guide the development of future spray coating systems and 3D printers.

Army Collaboration

Army research partners are vital to the ISN mission. They collaborate on basic and applied research, provide guidance on the soldier relevancy of ISN projects, and participate in transitioning (i.e., technological maturation and scale-up of the outcomes of ISN basic research). Since its founding, the ISN has collaborated with many Army science and technology laboratories and centers, including:

- Armament Research, Development, and Engineering Center
- Army Research Laboratory
    - Army Research Office
    - Computational and Information Sciences Directorate
    - Human Research and Engineering Directorate
    - Sensors and Electron Devices Directorate
    - Vehicle Technology Directorate
    - Weapons and Materials Research Directorate
- Aviation and Missile Research, Development, and Engineering Center
- Communications-Electronics Research, Development, and Engineering Center
    - Night Vision and Electronic Sensors Directorate

- US Army Corps of Engineers
- Edgewood Chemical/Biological Center
- Medical Research and Materiel Command
    - US Army Institute of Surgical Research
    - US Army Medical Research Institute of Infectious Diseases
    - US Army Medical Materiel Development Activity
    - US Army Research Institute of Environmental Medicine
    - Walter Reed Army Institute of Research
- Natick Soldier Research, Development, and Engineering Center
- Program Executive Office – Soldier
    - Project Manager – Soldier Protection and Individual Equipment

Other Department of Defense and Government Collaboration

While ISN's first customer remains the soldier, many ISN research projects are relevant to the needs of other government agencies. Collaborations and interactions have occurred with a number of the Army's sister services and other US government entities, including:

- Camp Roberts
- Deployed Warfighter Protection Program
- Naval Postgraduate School
- Naval Sea Systems Command
- US Air Force Medical Service
- US Air Force Special Operations Command
- US Department of Agriculture
- US Food and Drug Administration
- US Special Operations Command
- Walter Reed National Military Medical Center

Industrial Collaboration

Industry partners are critical to the ISN mission, helping turn innovative results of basic research into real products and scale them up for affordable manufacture in quantities needed by various end users. Current ISN industry partners include:

- Consortia for Improving Medicine with Innovation and Technology (CIMIT)
- JEOL USA, Inc.
- Lockheed Martin

- Nano-C
- Raytheon
- Total American Services
- Triton Systems
- Veloxint
- Xtalic

Outreach Activities

Soldier Design Competition

The ISN Soldier Design Competition (SDC) was established in 2003 to engage MIT undergraduates in the activities of ISN and, in 2004, was expanded to include cadets from the United States Military Academy at West Point (USMA). The SDC provides a unique opportunity for students to apply their knowledge and creativity while gaining hands-on experience in the design and prototyping of technology solutions to problems faced by today's soldier and first responder. Each year, a panel of leaders from the Army, industry, and MIT determines the winning technology solutions.

SDC participants meet active-duty soldiers and Marines and develop perspective on how modern technology can help the US military as well as firefighters, law enforcement officers, and other emergency response personnel. Army mentors provide SDC team members with advice on the military relevancy and technical viability of proposed technology solutions. Finalists are judged according to the technical design practicality, innovativeness, likely military benefit, and logistical supportability of their prototypes. Competitors are encouraged to further develop and commercialize their inventions.

The Finals of SDC15 in April 2018 were attended by a number of senior Army officials, including MG Cedric Wins, Commanding General of the US Army Research, Development, and Engineering Command. The winning team at the finals was a group of USMA cadets who developed a prototype blast-resistant plate armor for use on the undercarriage of military vehicles, such as the Bradley Fighting Vehicle. The team took home the first prize of $5,000 for their work.

The next cycle of the Soldier Design Competition (SDC16) will kick off in September 2018, and the finals event will be held on April 30, 2019.

With SDC16, the competition will enter an exciting new phase, as the ISN partners with MIT Lincoln Laboratory to rebrand the event as the ISN-Lincoln Laboratory Soldier Design Competition. Lincoln Laboratory will support a major portion of the competition's operating costs, and will serve as a venue for the finals in alternating years beginning with SDC17 in 2020.

Historically Black Colleges and Universities and Minority Institutions Program

In 2007, with Professor Paula Hammond as program director, the ISN began a program to engage faculty and students from historically black colleges and universities and minority institutions (HBCU-MIs) in research in support of the ISN mission. This initiative has funded peer-reviewed basic research projects at HBCU-MIs and facilitated collaborations between HBCU-MI and ISN researchers. Also, visiting faculty and students from HBCU-MIs have utilized ISN research facilities. During the reporting period, the ISN has funded two projects through its HBCU-MI program: one at the City College of New York, the other at Howard University.

Contributions to the MIT Community

ISN occupies approximately 40,000 square feet of space in a dedicated facility located in the northeast sector of the MIT campus within Cambridge's Technology Square. Since the beginning of the third ISN contract in 2013, more than 3,000 MIT personnel and affiliates have applied for and gained access to ISN research facilities. There are at any one time approximately 700 active registered users.

Users have access to ISN facilities that include wet and dry labs, computer clusters, and mechanical testing and other research instrumentation, including equipment for low- and high-rate mechanical characterization of the dynamic response of materials, electron microscopy, and femtosecond laser spectroscopy. Recently, the ISN has acquired a laser scanning confocal microscope, which provides non-contact, nanometer-scale profile, roughness, and film thickness data on a wide range of materials; an atomic layer deposition system, which is capable of conformal deposition of semiconductors, insulators, and metals on 3D objects; and a Zeiss Xradia 520 Versa X-ray tomography system, which compiles a series of very thin 2D scans of an object into a 3D image, performing similarly to the way a CT scan images biological tissue. Additionally, since the beginning of its second contract in 2007, the ISN has provided more than $9.5 million in seed and augmentation funding for MIT research projects, supporting research in a variety of different academic departments and research centers.

Also, ISN leadership engages with the broader MIT community through participation in various Institute committees. These have included the Lincoln Laboratory-Campus Interaction Committee, the Committee on Undergraduate Admissions and Financial Aid, the MIT-Department of Defense Engagement Group, the MIT Committee to Evaluate the Innovation Deficit, and the MIT.nano Governance Committee.

Future Plans

The ISN mission remains extremely relevant to the needs of the soldier and the nation. Over the coming years, the ISN will seek to build and further strengthen partnerships with the Army, other US military services, and industry while adjusting and enriching its basic research portfolio to respond to new opportunities and evolving customer needs. Working as an Army-industry-university team, the ISN continues to perform basic research and is transitioning to enable a range of innovative capabilities for the soldier, other US warfighters, and first responders.

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