Institute for Soldier Nanotechnologies

Founded in 2002, the Institute for Soldier Nanotechnologies (ISN) is a US Army University-Affiliated Research Center (UARC). The ISN was designed as a three-member team to leverage the unique capabilities of the US Army, industry, and the Massachusetts Institute of Technology. The ISN mission is to help the army and other US military services enable innovative capabilities for soldiers and other war fighters, their platforms and systems through basic research on nanotechnology by transitioning promising outcomes of that research in partnership with the army, other US military services, and industry. This mission includes not only decreasing the weight that soldiers and other war fighters carry but also 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 having been dispensed through a series of five-year contracts—ISN-1, ISN-2, and ISN-3—that were 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 by industry partners and MIT in ISN basic research.

Following extensive reviews leading to approval by the army in 2017, the ISN-4 research portfolio was enacted on January 1, 2018. ISN-4 has brought significant structural changes to the ISN, especially to 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 procurement contract for ISN-3, which sustains the ISN as a UARC, was extended 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 (DOD) for projects that are not part of the core ISN-4 portfolio. Additionally, there is a separate Cooperative Agreement (CA), new with ISN-4, that was established to fund the 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 more easily 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 augment its contributions to soldier and war fighter capabilities.

Thirty-five faculty members and research scientists representing more than 12 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, typically more than 350 people visit ISN each year for briefings on research endeavors and tours of ISN facilities. Of particular note, Major General James V. Young, Commanding General, 75th Training Command, visited the ISN in August 2018; members of the professional staff of the House Armed Services Committee visited the ISN in October 2018; and Major General Cedric T. Wins, Commanding General, US Army Combat Capabilities Development Command, visited in April 2019.

Headquarters Team

- Professor John D. Joannopoulos, Director, Francis Wright Davis Professor of Physics
- William A. Peters, Executive Director
- Professor Raúl A. Radovitzky, Associate Director, Raymond L. Bisplinghoff Professor of Aeronautics and Astronautics
- Franklin E. W. Hadley, Outreach and Communications Director
- Joshua Freedman, Assistant Director of Finance and Administration
- Ivan Celanovic, Principal Research Scientist
- Steve Kooi, Principal Research Scientist
- Amy Tatem-Bannister, Laboratory and Facilities Manager
- Kurt Keville, Research Specialist, Soldier Design Competition Coordinator
- Donna Johnson, Research Support Associate
- Maureen Caulfield, Finance Assistant
- Marlisha McDaniels, Executive Administrative Assistant
- John R. McConville, ARL-ARO Technology Transfer Officer

Over the past year, one longtime member of the ISN team and MIT community, research specialist William DiNatale, departed due to retirement. A search for his successor is in progress.

Research Portfolio

The ISN's signature interdisciplinary research agenda evolved over the course of its first 15 years into a focused program reflecting the areas where ISN and the army see the potential for especially strong 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 working within the constraints of army budget reductions. Team-based innovation is a hallmark of ISN's intellectual course, with new ideas and collaborations emerging frequently. The ISN research portfolio is currently divided into three strategic research areas (SRAs), which are further divided into specific projects.

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

- Project 1.1: Advanced Multiscale Methods for Modeling of Fracture in Novel Nanomaterials
  PIs: Raúl Radovitzky (Department of Aeronautics and Astronautics [AeroAstro]), Keith Nelson (Department of Chemistry [Chemistry]), and Xuanhe Zhao (Department of Mechanical Engineering [MechE])
- Project 1.2: Shock Mitigating and Reinforcing Molecular Nanocomposites
  PI: Michael Strano (Department of Chemical Engineering [ChemE])
- Project 1.3: Design and Testing of Polymers for Improved Soldier Protection
  PIs: Keith Nelson (Chemistry), Tim Swager (Chemistry), and Greg Rutledge (ChemE)
- Project 1.4: Superelastic Granular Materials for Impact Absorption
  PIs: Chris Schuh (Department of Materials Science and Engineering [DMSE]), Raúl Radovitzky (AeroAstro), and Kenneth Kamrin (MechE)
- Project 1.5: Rapid Hemostasis for the Treatment of Incompressible Wounds
  PIs: Bradley Olsen (ChemE), Paula Hammond (ChemE), and Shuguang Zhang (MIT Media Lab; Center for Bits and Atoms)
- Project 1.6: Empowering Future Vaccines and Immunotherapies with Nanotech-Based Adjuvants
  PI: Darrell Irvine (DMSE; Department of Biological Engineering)

Strategic Research Area 2: Augmenting Situational Awareness

- Project 2.1: Uncovering Chemical Stability and Charge Transfer Mechanisms at Electrode-Electrolyte Interfaces
  PI: Bilge Yildiz (Department of Nuclear Science and Engineering; DMSE)
- Project 2.2: Mid- and LW-Infrared Detector Arrays on Flexible Substrates
  PIs: Tomás Palacios, Dirk Englund, and Jing Kong (all from the Department of Electrical Engineering and Computer Science [EECS])
- Project 2.3: Room Temperature LWIR-THz Detection via E-Field Enhancement Induced Quantum Dot Upconversion
  PIs: Moungi Bawendi (Chemistry), Vladimir Bulović (EECS), Keith Nelson (Chemistry), and Adam Willard (Chemistry)
- Project 2.4: Particulate Fluid Fiber Processing for Fabric Communications
  PIs: Yoel Fink (MechE; EECS), John Joannopoulos (Department of Physics [Physics]), and Alexander Stolyarov (MIT Lincoln Laboratory)
- Project 2.5: Nano-Plasmonics for Soldier Applications
  PIs: Marin Soljačić (Physics), Jing Kong (EECS), and Steven Johnson (Department of Mathematics [Math])

Strategic Research Area 3: Transformational Nano-Optoelectronic Soldier Capabilities

- Project 3.1: Solid State Power Generation at Millimeter Scales
  PIs: Ivan Celanovic (ISN), Marin Soljačić (Physics), and Peter Fisher (Physics)
- Project 3.2: Photonic Integrated Circuits for LIDARs, Displays and Low-Power Computing
  PIs: Dirk Englund (EECS), Marin Soljačić (Physics)
- Project 3.3: Nanophotonics Enhanced Systems for the Soldier
  PIs: Steven Johnson (Math), Marin Soljačić (Physics), and John Joannopoulos (Physics)
- Project 3.4: Applications of Novel Topological Phenomena
  PIs: Liang Fu, Nuh Gedik, and Marin Soljačić (all from Physics)
- Project 3.5: Novel Multimaterial Inks for Multiscale 3D Device Printing
  PIs: Yoel Fink (DMSE; EECS), with significant contributions from Alexander Stolyarov (MIT Lincoln Laboratory)

In addition to these core projects, the ISN occasionally receives additional funding from the army and other US military services to perform research, and also uses MIT cost-sharing and industry support funds to enable seed projects on promising work.

Transitioning

The ISN places a strong emphasis on basic research. However, the transitioning, or technology transfer, of promising outcomes of that research 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 with the MIT Technology Licensing Office to help assure that promising ISN innovations leave the lab and benefit soldiers, other war fighters, and first responders as rapidly and efficiently as possible. The ISN is pleased to count John R. McConville, a US Army Combat Capabilities Development Command (CCDC) ARL-ARO Technology Transfer Officer (TTO), among our full-time headquarters team. 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 as a part of the National Network for Manufacturing Innovation and based on a proposal spearheaded by MIT, AFFOA is rooted in foundational ISN research that is led by ISN-affiliated MIT faculty member Professor Yoel Fink. In June 2017, AFFOA unveiled its dedicated facilities a short walk from the main MIT campus, along with a sampling of prototypes containing advanced optoelectronic fiber devices. AFFOA counts the following among its senior leadership team: Chief Executive Officer Yoel Fink, who is an ISN PI; Chief Operating Officer Tairan Wang, who contributed to ISN research as a postdoctoral researcher; Chief Technology Officer Aimee Rose; Chief Engineer Jason Cox; Defense Technology lead Alexander Stolyarov; and Senior Product Engineer Mihai Ibanescu.

Sample ISN Research Accomplishments

NMR-Based Hydration Status Monitoring

Led by the ISN-affiliated David H. Koch Professor of Engineering Michael Cima, a team of researchers from MIT, Massachusetts General Hospital, and Harvard Medical School, has devised a novel means of assessing a person's hydration status. Based on the same nuclear magnetic resonance phenomena exploited in a magnetic resonance imager (MRI), this new technology returns results both more quickly and more economically than an MRI as there is no need to translate measurements into images. Furthermore, because the magnetic resonance signal in the body obtained in this technology comes exclusively from hydrogen atoms, and almost all hydrogen atoms in the body are from water, the measurements are vastly more accurate than traditional methods of assessing human hydration. Initially, this approach has been tailored to assist the monitoring of hydration state of dialysis patients, but it could eventually be extended for use with the elderly, athletes, and war fighters, all of whom can be prone to dehydration. Details of this research are presented in an article published in the journal *Science Translational Medicine*. In addition to this recent success, a group of Professor Cima's students competed in 2016's 14th Soldier Design Competition, taking home third prize for an earlier version of this same technology.

Implosion Fabrication of Complex 3D Nanostructures

By reversing the expansion microscopy technique that they conceived just a few years ago, a team led by ISN-affiliated MIT faculty member, Professor Ed Boyden has devised a groundbreaking implosion fabrication process. This new technology uses a preswelled hydrogel as a scaffold to which anchors have been connected through a two-photon microscopy process. A vast array of materials can be attached to the anchors. When acid is used to shrink the hydrogel scaffold, the anchored structure contracts with it, shrinking by as much as 90% in each dimension for a volume that is one thousandth that of the original. The research team foresees specialized lenses as an initial route of productization, potentially leading to improved cell phone cameras, but believes more complex systems could be made in the future as fabrication resolution improves. Further details of this research are presented in an article published in the journal *Science*.

Ultrafast, Sub-Attojoule Matrix Multiplication via Photonic Accelerator

As detailed in a recent article in the journal *Physical Review X*, Professors Marin Soljačić and Dirk Englund with their team of students and other researchers have devised a new photonic accelerator chip that uses light rather than electrons to increase the speed and efficiency of the complex matrix multiplication functions necessary for the training of artificial intelligences based on deep neural networks. Fully realized, the system would be capable of achieving gigahertz speeds while consuming sub-attojoule energies per multiply and accumulate function. Eventual applications of this technology could abound in areas where the fast, highly accurate, and more energy efficient handling of large amounts of data is critical, including imaging, language processing, object identification, drug development, and the control and navigation tasks of driverless vehicles.

Harvesting Electricity from Wi-Fi Signals

A team of MIT researchers, including ISN-affiliated Professors Jing Kong and Tomás Palacios, working with scientists from the CCDC Army Research Laboratory, has invented the first fully flexible device to harvest the energy of Wi-Fi signals and convert them into usable electricity. Devices for converting AC electromagnetic waves into DC electricity, known as rectennas, have existed for decades, but advances in their materials are making them much faster, allowing for the new devices to cover broader frequency ranges, including the range of Wi-Fi. Full foldability could allow for their incorporation into a much greater variety of systems. Detailed information on this work is available in a recent article published in the journal *Nature*.

Toward Cleaner, Wrinkle-Free Graphene

Standard methods of transferring graphene from its growth substrate to its destination substrate involve coating it in a polymer that must then be removed once the graphene is settled. Unfortunately, this process regularly imparts flaws and wrinkles that degrade the graphene's electrical performance. Now, a new process developed by ISN faculty members Tomás Palacios and Jing Kong that uses paraffin wax shows promise to dramatically reduce these imperfections. Replacing a coating of polymethyl methacrylate with one of wax has led to a simplified transfer and also to reduced wrinkling and minimized surface defects. Future plans include further reducing flaws and expanding the technique to other 2D materials. An article on the work was recently published in the journal *Nature Communications*.

Cataloging Antimolecules

Tiny defects, or holes, that form in sheets of 2D materials can change their electronic, magnetic, and mechanical properties. However, with some 400 billion possible arrangements resulting from the loss of just 30 atoms in a lattice, mapping them all is unfeasible. Now, a team led by ISN-affiliated professor Michael Strano has largely solved this issue by cataloging and describing such holes, which the team calls antimolecules, that are most likely to appear under a given set of circumstances as opposed to the overwhelming set of theoretically possible configurations, most of which will never be found in experiments. Having a more realistic appraisal of antimolecule configurations could affect a variety of potential applications, from barrier membranes, to filtration systems, to DNA sequencing. Details of this work are available in a recent article published in the journal *Nature Materials*.

Structural Color in Drops of Water

A team that includes ISN-affiliated MIT professor Mathias Kolle has discovered a phenomenon that causes droplets of water lit by white light to produce strongly colored iridescence. Rather than resulting from Mies scattering, which causes rainbows, this coloration is caused by total internal reflection of light inside the droplet. The team was able to model and predict the geometries necessary for specific colors, and was even able to trigger the same style of coloration in 3D printed transparent polymer domes and dots. The team thinks that it may be able to harness the technique to replace potentially harmful dyes, in makeup products, and even in novel, color-changing applications. Technical information on this research is available in a recently published article in the journal *Nature*.

Improved 2D Patterning and Fabrication

While potential uses for circuitry enabled by 2D materials continue to increase, a roadblock to their widespread adoption has been the complexity of their manufacture. Now, a team including ISN-affiliated MIT professors Jing Kong and Tomás Palacios has developed a new technique that greatly simplifies the process by depositing 2D materials directly onto patterned substrates, while also allowing the substrates to be reused rather than discarded. A field-effect transistor created using the new process has already demonstrated performance comparable with devices created using earlier methods. Research is planned to improve spatial resolution of the fabrication technique. More details are available in an article published in the *Proceedings of the National Academy of Sciences*.

Army Collaboration

Army research partners are vital to the ISN mission. They collaborate with the ISN on basic and applied research, provide guidance on the relevancy of ISN projects, and participate in transitioning (i.e., technological maturation and scale-up of the outcomes of ISN basic research). A sampling of army science and technology laboratories and centers with which the ISN has collaborated is listed below. With the 2018 creation of the four-star US Army Futures Command (AFC), many army S&T organizations have been renamed under the banner of AFC or its major subordinate reporting units, such as the two-star US Army Combat Capabilities Development Command. In such cases, the organizations' previous names are included in parenthesis CCDC Armaments Center (Armament Research, Development, and Engineering Center).

- CCDC 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
- CCDC Chemical/Biological Center (Edgewood Chemical/Biological Center)
- Medical Research and Matériel Command
    - US Army Institute of Surgical Research
    - US Army Medical Research Institute of Infectious Diseases

  - US Army Research Institute of Environmental Medicine
  - Walter Reed Army Institute of Research
- CCDC Soldier Center (Natick Soldier Research, Development, and Engineering Center)
- Program Executive Office—Soldier
  - Project Manager—Soldier Protection and Individual Equipment

Other Department of Defense and US Government Collaboration

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

- Camp Roberts
- Deployed War Fighter 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. Recent ISN industry partners have included the following:

- Nano-C
- Raytheon
- 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. 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 soldiers and first responders. Each year, a panel of leaders from the army, industry, and MIT determines 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 fire fighters, police 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 SDC16 in April 2019 were attended by a number of senior army officials, including Major General Cedric Wins, Commanding General of the US Army Research, Development, and Engineering Command, who was the senior military guest at the event. The winning team at the finals was a group of MIT graduate students who developed a prototype chip-scale LIDAR array requiring much less power than current lens-based, puck-style designs. Eventually, systems incorporating this innovation could enable more versatile imaging technology. The team received the first prize of $5 thousand for their work.

The next cycle of the SDC17 will kick off in September 2019, and the finals event will be held on April 28, 2020.

With SDC16, the competition entered an exciting new phase, in which it became a collaborative effort of the ISN and MIT Lincoln Laboratory and renamed the ISN-Lincoln Laboratory Soldier Design Competition. The ISN and Lincoln Laboratory each provide a major portion of the competition's operating costs. Beginning with SDC17, the venue for the competition finals will alternate between Lincoln Laboratory and the MIT campus.

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, and electron microscopy. Additional ISN equipment available to qualified MIT users includes a laser scanning confocal microscope, which provides noncontact, 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; 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; and the newest addition to the ISN equipment roster, a Zeiss Sigma 300 field emission scanning electron microscope with integrated plasma cleaner and solid-state, backscattered electron detector.

Additionally, since the beginning of its second contract in 2007, ISN has provided more than $10 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-DOD 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 soldiers, other US war fighters, first responders, and the nation. Over the coming years, ISN will seek to build and further strengthen partnerships with the army, other US military services and agencies, and industry while adjusting and enriching our basic research portfolio to respond to new opportunities and evolving customer needs. Working as an army-industry-university team, we will continue to perform basic research and transitioning to enable a range of innovative capabilities to protect and assist US military personnel and civilians in high-risk and dangerous situations.

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