Institute for Soldier Nanotechnologies

Founded in 2002, the Institute for Soldier Nanotechnologies (ISN) is a three-member team designed to leverage the unique capabilities of the US Army, industry, and MIT. The ISN mission is to help the Army dramatically improve the survivability of the soldier by working at and extending the frontiers of nanotechnology through basic research and transitioning promising outcomes of that research in collaboration with our Army and industry partners. This mission includes not only decreasing the weight that soldiers carry but also improving blast and ballistic protection, creating new methods of detecting and detoxifying chemical and biological threats, and providing physiological monitoring and far-forward medical treatment. The ultimate goal is to help the Army create an integrated system of nanotechnologies that combines high-tech protection and survivability capabilities with low weight and increased comfort.

Army funding for ISN basic research is approximately $150 million over 15 years, dispensed through renewable five-year contracts administered by the US Army Research Office. There is also substantial co-investment by industry partners and MIT. Following a series of reviews by the Army, ISN was approved for the renewal of its five-year contract in 2012. The contract for ISN-3 was signed on December 27, 2012.

Each year approximately 50 faculty members from 12 MIT academic departments, as well as approximately 100 graduate students and 50 postdoctoral associates, participate in ISN research, producing more than 150 refereed publications in distinguished scientific journals such as *Science*, *Advanced Materials*, and the *Proceedings of the National Academy of Sciences*. Additionally, more than 500 people visited ISN over the past year for briefings on research endeavors and tours of ISN facilities. On November 14, 2013, ISN was privileged to host the Army chief of staff, General Raymond Odierno. On June 25, 2014, ISN held its biennial research overview meeting, colloquially known as ISN Day, at which deputy assistant secretary of the Army Mary Miller delivered a keynote address about the Army's science and technology efforts.

Research

ISN's signature interdisciplinary research agenda evolved over the course of its first 10 years into a focused program reflecting the areas where ISN and the Army see the potential for especially strong soldier impacts. This structure has remained substantially intact for the ISN-3, although specific areas have been repositioned and redefined to better align with and more efficiently respond to Army needs. Team-based innovation is a hallmark of ISN's intellectual course, with new ideas and collaborations emerging frequently. The ISN research portfolio is divided into five Strategic Research Areas (SRAs) that are, in turn, further divided into themes and then specific projects.

Strategic Research Area 1: Lightweight, Multifunctional, Nanostructured Materials and Hybrid Assemblies

SRA 1 emphasizes the creation of nanoscale and nanostructured building blocks to provide diverse protective capabilities such as sensing, communications, night vision, electronic devices, and visibility management. Examples of these building blocks are

nanocrystals (quantum dots), novel carbon forms (graphenes, carbon nanotubes), optoelectronic fibers, coatings, interfaces, and hybrid nanostructures.

- Theme 1.1: Quantum Dots for Wide-Bandwidth Imaging and Communications
  - Project 1.1.1: Hybrid Quantum Dot-Based Imagers and Emitters with Broadly Tunable Spectral Characteristics
- Theme 1.2: Nanoscale Carbon Forms for Situational Awareness
  - Project 1.2.1: Graphene Devices for Next-Generation Night Vision Systems
- Theme 1.3: High-Functionality Nanostructured Surface Capabilities
  - Project 1.3.1: Nanostructured Hybrid Interfaces
  - Project 1.3.2: Responsive Surface Texturing and Coloring
  - Project 1.3.3: Enabling Architectures and Technologies for Next-Generation Fiber Devices
- Theme 1.4: Environmental Obfuscation and Extended-Reach Situational Awareness
  - Project 1.4.1: Tailored Nanoparticles for Obscurant Applications

Strategic Research Area 2: Soldier Medicine—Prevention, Diagnostics, and Far-Forward Care

SRA 2 focuses on medical diagnostics and treatment for the soldier with a particular emphasis on enabling far-forward and remote area care, including immediate as well as longer-term treatment of battlefield injuries (e.g., through drug preservation and delivery, treatment of hemorrhagic shock, wound healing, and neuromedicine).

- Theme 2.1: Disease Prevention: Nanoengineered Drug Delivery and On-Demand Protection
  - Project 2.1.1: Nanotechnology for Stimulating, Sampling, and Monitoring Immunity
- Theme 2.2: Drug Preservation, Dose Preformulation, and Far-Forward Administration
  - Project 2.2.1: Rapid Reconstitution Packages of Lyophilized Medicines
- Theme 2.3: Materials and Devices for Emergency and Long-Term Treatment of Battlefield Injuries
  - Project 2.3.1: Nanostructured Biomaterials for Treatment of Hemorrhagic Shock
  - Project 2.3.2: Multicomponent Nanolayer Assemblies for Soldier Wound Healing
  - Project 2.3.3: Delivery of Brain Lipid Nanoparticles Using Microtech Devices for Treatment of Traumatic Brain Injury
  - Project 2.3.4: Complementary Wound-Healing Strategies Enabled by Synthetic Biology and Nanotechnology

Strategic Research Area 3: Multiple Blast and Ballistic Threats—Materials Damage, Human Injury Mechanisms, and Lightweight Protective Systems

The aim of SRA 3 is to develop new, lighter-weight protective materials systems for improved protection from blast, ballistic, and blunt trauma, as well as to increase understanding of materials failure and human injury due to blast and other forms of mechanical energy. This understanding is, in turn, used to guide the design and formulation of novel protective materials with potential applications for the dismounted and the mounted soldier.

- Theme 3.1: Nanoengineered Composites and Fibers for Ballistic, Blast, and Blunt Trauma Protection
  - Project 3.1.1: Nanocomposite Metamaterial Architectures for Guiding Energy Dissipation and Wave Propagation
- Theme 3.2: Metallic Alloys, Fibers, and Fabrics for Protection and High-Capacity Mechanical Energy Damping
  - Project 3.2.1: Layered/Graded Nanocrystalline and Superelastic-Fiber Alloys for Lightweight Protection
- Theme 3.3: Blast-Induced Injury: Physical Mechanisms, Biological Responses, and Physiological Outcomes
  - Project 3.3.1: Blast-Induced TBI—Connections Among the Physical, Biological, and Behavioral Dimensions
  - Project 3.3.2: Electromechanical Interactions in Blast-Induced Traumatic Brain Injury
  - Project 3.3.3: Molecular to Macroscale Exploration of Fundamental Properties of Gels
  - Project 3.3.4: Predictive Multiscale Deformation and Injury of Soft Tissues
- Theme 3.4: Multiscale Modeling, Simulation, and Measurements of Blast and Ballistic Damage to Protective Materials and Systems
  - Project 3.4.1: Advanced Computational Tools for Multiscale Modeling and Simulation of Multithreat Protective Systems
  - Project 3.4.2: High-Performance Woven Fabrics and Woven Reinforced Composites for Soldier Protective Systems
- Theme 3.5: Advanced Concepts for Lightweight, Flexible Protective Materials
  - Project 3.5.1: Biological and Bio-inspired Reconfigurable Flexible and Protective Joints
  - Project 3.5.2: Design and Synthesis of Carbon-Based Chainmaille Structures for Flexible, Ultra-Lightweight Protection

Strategic Research Area 4: Hazardous Substances Sensing, Recognition, and Protection

SRA 4 focuses on exploring and enabling new mechanisms for the high-sensitivity detection of molecularly complicated hazardous substances such as chemical and biological agents, food-born pathogens, and explosives, as well as individual toxicants in complex organic mixtures. This SRA also focuses on methods to detect human exposure to toxins and to protect humans from hazardous biological substances such as viruses and bacteria.

- Theme 4.1: Sensing of Toxic Substances, Exposure Biomarkers, and Explosives Using Integrated Nanostructured Platforms
  - Project 4.1.1: Graphene Sensing for Detection of Foodborne and Other Pathogens
  - Project 4.1.2: Resistivity-Based Microfluidic Biosensing
  - Project 4.1.3: Rugged, High-Sensitivity, Integrated Photonic Chemical Sensing
  - Project 4.1.4: Molecular Recognition Using Carbon Nanotube Adsorbed Polymer and Bio-Polymer Phases: Synthetic Nanotube Templated Antibodies
- Theme 4.2: Quantum Dots for Chemical/Biological Sensing
  - Project 4.2.1: Chemical-Biological Analyte Sensing with Hybrid Quantum Dot Constructs

Strategic Research Area 5: Nanosystems Integration for Protected Communications, Diagnostic Sensing, and Operational Flexibility in Complex Environments

The goal of SRA 5 is the integration of nanoscale and nano-enabled materials and devices into systems that provide the soldier with enhanced flexibility to operate in complex environments (e.g., through capabilities to sense toxic chemicals, pressure, and temperature; shield electronics from electromagnetic interference; and detect sound and other mechanical vibrations) and allow groups of soldiers to communicate free of enemy eavesdropping.

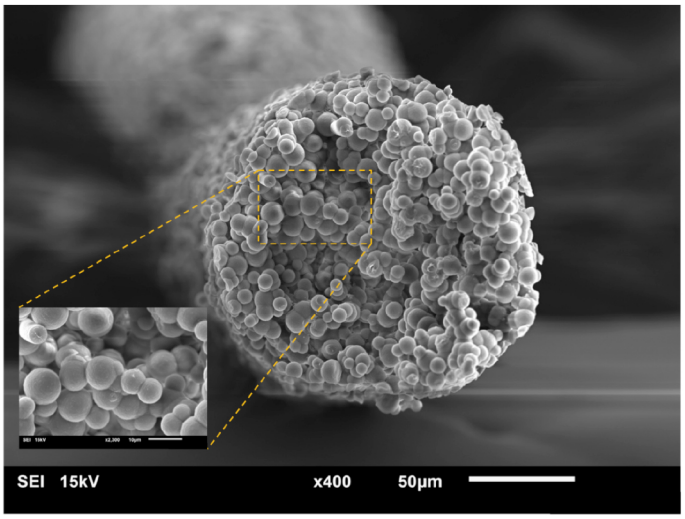
- Theme 5.1: Optoelectronic Fiber Platforms with Real-Time Modulation Capabilities
  - Project 5.1.1: Ferroelectric Acoustic Fibers
- Theme 5.2: Multicapability Systems for Communications, Sensing, and Signal Processing
  - Project 5.2.1: Multifunctional Integrated Fabrics
  - Project 5.2.2: Enabling Novel Lightwave Phenomena
  - Project 5.2.3: Spatial Awareness Around Corners
- Theme 5.3: Lightweight Power and Energy for Enhanced Uniform Functionality and Protection
  - Project 5.3.1: Novel Thermal Radiation Management Using Advanced Photonic Crystals

Transitioning

ISN places a strong emphasis on basic research. However, the transitioning of promising outcomes of that research is also a crucial component of our mission. To this end, ISN works with the Army, industry partners, startups and other companies, and the MIT Technology Licensing Office to help ensure that promising ISN innovations leave the lab and make it into the hands of soldiers and first responders as rapidly and efficiently as possible. ISN is pleased to count a technology transfer officer (TTO) from the Army Research Office 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.

A Small Sampling of ISN Research Accomplishments and Transitions

Optoelectronic Fibers



Scanning electron microscope image of the cross section of a porous PVdF fiber after cladding removal and solvent drying.

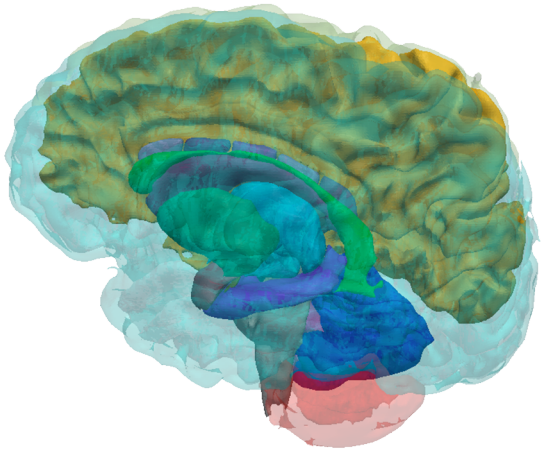
Unlike traditional approaches for making "smart" fabrics, which center on attaching devices to conventional woven materials, this ISN research focuses on the development of unique fibers that are themselves optoelectronic devices. Already, fibers have been produced that detect light, heat, and sound. Future applications could include combat identification, infrared communications, sniper detection, medical imaging, and blast and blunt impact monitoring. Previously, a hollow fiber that internally guides CO2 laser light with essentially no attenuation was transitioned to startup company OmniGuide and is being used in approximately 1,000 civilian and Veterans Administration hospitals across the United States to perform more than 2,400 endoscopic surgeries every month.

Recently, researchers have begun to harness the potential of in-fiber chemistry, synthesizing in situ silicon by co-drawing aluminum and quartz. They have also been able to produce porous domains inside thermally drawn fibers and, through capillary instability, silica-clad spheres subject to tremendous pressure.

Detection of Hazardous Substances

ISN faculty and researchers have pioneered the development of a novel class of molecular chromophore systems called amplifying fluorescent polymers (AFPs). These AFPs, long molecules that glow under certain conditions, enable ultra-high-sensitivity detection of explosives and other hazardous materials. In partnership with FLIR Systems and (previously) ICx Technologies and ICx Nomadics, devices incorporating AFPs have been developed and fielded in Iraq and Afghanistan. A variation of this technology has been transitioned to the Transportation Security Administration for the detection of liquid explosives at airports. Recent advancements in this area have related to multi-analyte detection through incorporation of numerous discrete sensing capillary fibers.

Blast and Ballistic Protection

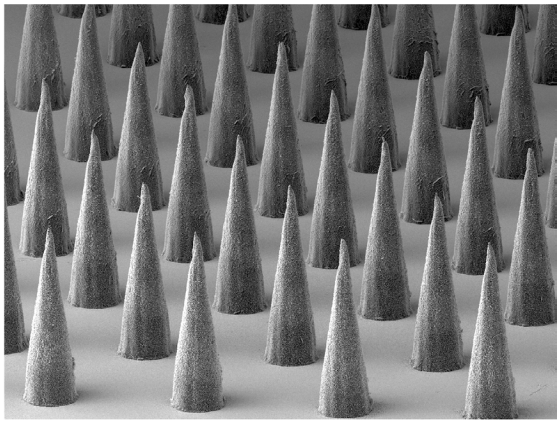


Three-dimensional reconstructed brain model from MRI structural data.

By capitalizing on unique deformation mechanisms that exist at the nanoscale, ISN is developing materials with increased strength and energy dissipation characteristics. One example is the fabrication of nanoparticle metal alloys that combine the high strength of steel with the low weight and high ductility of aluminum. These alloys have been transitioned to the Army Research Laboratory (ARL); the Army Armament Research, Development, and Engineering Center; and MIT startup Xtalic for scale-up, testing, and further development.

While the development of advanced protective materials is a vital component of ISN research, it is also necessary to understand how materials fail, how to improve materials to make them stronger and lighter, and what happens behind armor exposed to a strong mechanical force. ISN is investigating all of these questions through the development of high-fidelity predictive mathematical modeling and simulation tools. A key example is an ISN collaboration with the Army to construct an extremely realistic human head and helmet model in order to explore the effect of blast wave impacts (e.g., from improvised explosive device explosions) on the soldier. Recent efforts in this realm have focused on the incorporation of magnetic resonance imaging structural data into modeling methodologies.

Health Monitoring, Protection, and Treatment



Hydrogel-coated microneedles contain ICMV nanocapsules.

Nanostructured materials hold extraordinary potential for improved medical care. In a joint ISN-Army malaria vaccine study using a murine model, a newly developed ISN nanoparticle, called an interbilayer-crosslinked multilamellar vesicle (ICMV), provided a tenfold increase in immune response with 100 times less vaccine. Moreover, the immune response remained essentially unchanged for over one year. A new MIT startup company, Vedantra Pharmaceuticals, has been created to transition this technology to the marketplace.

In addition, rapid reconstitution packages of lyophilized drugs have been developed to greatly simplify logistics, dramatically prolong drug shelf life, and increase ease of administration in the field.

Wireless Power

Although the feat was long thought impossible, ISN faculty and researchers were able to transmit electric power wirelessly and nonradiatively over a distance of two meters using two strongly coupled magnetic resonators. Startup company WiTricity is developing this technology. Moreover, Army scientists at the Natick Soldier Research, Development, and Engineering Center are investigating applications to power helmet-mounted devices without connecting wires, while the Army's Rapid Equipping Force, in collaboration with ISN partner QinetiQ North America, is researching the remote charging of robots. Recent WiTricity advances that enable the transfer of 3.3 kW over a distance of one-half meter at more than 90% efficiency have opened the possibility of the cordless charging of electric vehicles.

Historically Black Colleges and Universities and Minority Institutions Program

In 2007, with professor Paula Hammond as program director, 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 program funds peer-reviewed basic research projects at HBCU-MIs and facilitates collaborations between HBCU-MI and ISN scientists. Also, visiting faculty and students from HBCU-MIs utilize ISN research facilities.

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). ISN maintains substantial interactions with many Army science and technology laboratories and centers, including:

- Armament Research, Development, and Engineering Center at Picatinny Arsenal
- Army Research Laboratory (including the Army Research Office, Computational and Information Sciences Directorate, Human Research and Engineering Directorate, Sensors and Electron Devices Directorate, and Weapons and Materials Research Directorate)
- Aviation and Missile Research, Development, and Engineering Center
- Communications-Electronics Research, Development, and Engineering Center
- Defense and Veterans Brain Injury Center
- Edgewood Chemical/Biological Center
- Madigan Army Medical Center
- Natick Soldier Research, Development, and Engineering Center
- Program Executive Office Soldier
- Tank Automotive Research, Development and Engineering Center
- US Army Corps of Engineers
- US Army Research Institute of Environmental Medicine
- Walter Reed Army Institute of Research

Other Department of Defense and Government Collaboration

While ISN's first customer remains the Army, ISN also has had substantial interactions and collaborations with a number of the Army's sister services and other US government entities, such as:

- 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 membership of the ISN Industry Consortium includes:

- Center for Integration of Medicine and Innovative Technology
- FLIR Systems
- JEOL USA
- Lockheed Martin
- Nano-C
- Nike
- Raytheon
- Total American Services
- Triton Systems
- VF Corporation
- 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. In 2004, the competition 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 soldiers and first responders. Teams compete for prize money donated by industry companies that have included Boeing, General Dynamics, L-3 Communications, Lockheed Martin, QinetiQ North America, Raytheon, and W.L. Gore and Associates. Each year, a panel of leaders from the Army, industry, and MIT determines winning prototypes.

Teams address challenges supplied by the Army and Marine Corps science and technology, acquisition, and operations communities. 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 winning team at SDC 11 was a group of MIT students who developed an improved tourniquet for emergency use in the field. Utilizing a novel quick-cinch mechanism and an articulated one-way buckle, the THOR Tourniquet can be applied one handed on trapped limbs much more rapidly than other models currently in use by military and civilian emergency medical technicians. The THOR team took home the first-place Lockheed Martin Prize of $7,000 for their work. Another MIT team was awarded second place, and the $5,000 Raytheon Prize, for creating the ResQ Warmer, a simple device to help warm intravenous fluids in the field.

Army Nanotechnology Seminar Presentations

The ISN Army Nanotechnology Seminar (ANTS) series is designed to foster exchange of information related to research on soldier protection, equipment, health, and other needs. These seminars also offer ISN researchers, graduate students, and postdoctoral associates the opportunity to learn more about research under way at Army labs and other facilities.

To help our colleagues at other locations participate, seminars are webcast using collaboration software that facilitates real-time interaction. Remote participants can watch and listen to presentations and engage in Q&A.

There was a minimized ANTS schedule in 2013–2014, with only two seminars, but a reinvigorated series is planned for 2014–2015.

Summer Internships

In 2008, working with Army colleagues at ARL, ISN began a summer internship program to provide MIT students with opportunities to perform research at Army laboratories under the guidance of Army scientists. Marlisha McDaniels of the ISN headquarters team is program coordinator.

MIT students gain an introduction to cutting-edge Department of Defense (DoD) research at world-class Army laboratory facilities while forging new professional relationships and discovering potential career opportunities within the DoD science and technology community. ISN and the Army co-invest to cover student salaries and living expenses.

In the summer of 2014, 14 internships at 10 different Army labs were available through the program. Twenty-four students showed interest, and three were chosen to work at two Army labs. More than 40 Army scientists expressed interested in mentoring and signed up via an online system that allowed them to post opportunities available at their labs.

ISN also participates in the West Point Advanced Individual Academic Development program, under which ISN welcomes cadets from the USMA Department of Systems Engineering who engage in short-term research projects.

ISN Website and Partner Portal

The newly redesigned ISN website, with an integrated portal for ISN industry partners and Army collaborators.

Over the course of the past several years, ISN developed and implemented the ISN Industry Collaboration Portal, a password-protected information-sharing wiki designed to help better inform ISN constituents of new and emerging research, recent and upcoming visitors, and important events. The Industry Collaboration Portal was a standalone site, independent of the main ISN website. In early 2014, a completely redesigned ISN website was activated that includes an enhanced Partner Portal, with protected access provided to the primary points of contact for each ISN partner company as well as to others as requested. The integrated Partner Portal effectively replaces the Industry Collaboration Portal, improving upon both its amount of information and its ease of use.

Contributions to the MIT Community

ISN maintains over 40,000 square feet of space in a dedicated facility located in Cambridge's Technology Square. More than 450 registered users from across MIT have access to ISN facilities that include wet and dry labs, computer clusters, and mechanical testing and other research instrumentation such as equipment for low- and high-rate mechanical characterization of the dynamic response of materials, electron microscopy, and femtosecond laser spectroscopy.

Additionally, since the start of the second ISN contract in August 2007, ISN has provided more than $5.5 million in seed and augmentation funding for MIT research projects.

Future Plans

The ISN mission remains extremely relevant to the needs of the soldier and the nation. Over the coming years, ISN will seek to build and further strengthen partnerships with the Army, other US military services, and industry, refocusing and streamlining our portfolio of basic research projects while exploring the potential for additional funding. Working as an Army-industry-university team, we will continue to perform basic research and transitioning to improve soldier protection and survivability.

John D. Joannopoulos
Director
Francis Wright Davis Professor of Physics