Institute for Soldier Nanotechnologies

Now in its fifth year, the Institute for Soldier Nanotechnologies (ISN) continues to strengthen its innovative research program and has recently submitted plans for the renewal of its five-year contract.

Through basic research and collaboration with industry and the US Army in technology development, the ISN mission is to provide a dramatic increase in survivability to the individual soldier through the use of novel nanoengineered materials and devices in a significantly lighter weight uniform. This includes reducing the weight soldiers carry, improving blast and ballistic protection, creating new methods for detecting and detoxifying chemical and biological threats, and providing physiological monitoring and automated medical intervention. The ultimate goal is to create a multifunctional 21st-century battlesuit that combines high-tech protection and survivability capabilities with light weight and comfort.

During the past year, ISN has hosted over 400 visitors from the military, industrial, and academic sectors, including several senior leaders from the Army. ISN has hosted thematic workshops and continued its successful seminar series. The MIT Soldier Design Competition completed its third year, once again drawing on the engineering talents of undergraduates from both MIT and the US Military Academy at West Point (USMA).

ISN's estimated five-year funding now stands at more than $95 million in cash and in-kind contributions, with the Army contributing approximately $47.5 million in basic research (category 6.1) funding and an estimated $12.5 million in applied research (category 6.2) funding (to industry partners and collaborating Army labs), MIT providing $13.9 million (not including the cost of the dedicated facility, which was estimated at $9.3 million), the founding industrial partners contributing $15.3 million, and new industry partners providing approximately $6.7 million.

Research

More than 35 basic and applied research projects are currently under way at the Institute for Soldier Nanotechnologies. ISN researchers published 69 technical papers during the year, with another 20 accepted and awaiting publication. To date, ISN has published 192 research papers and 33 technology disclosures.

Team-based innovation is a key part of ISN's approach to complex problems like protecting tomorrow's soldiers from diverse military and environmental threats. Seven research teams address various aspects of the overall challenge. The following subsections discuss the research goals of these teams, as well as provide a sample of specific research projects from each.

Team 1: Energy-Absorbing Materials

Energy-absorbing material systems that will protect the future soldier against ballistic impact and blast waves are a critical piece of the overall ISN mission. Using new polymers as well as designs of nanocomposites and mesocomposites, Team 1 is working to design, synthesize, and fabricate materials that provide revolutionary properties to protect soldiers from blast waves and ballistic fragments and yet are still lightweight and flexible enough to maintain soldier mobility. Such materials must also have the capacity to be integrated with and to protect the other components in the future soldier's battlesuit, such as the sensors and biological protection features that Teams 3 and 4 are developing.

Led by Professor Ned Thomas from the Department of Materials Science and Engineering (MSE), Team 1 faculty investigators are from the Departments of Chemistry, MSE, Mechanical Engineering (ME), and Chemical Engineering (CE).

Professors Thomas and Mary Boyce (ME) are developing novel microtruss polymeric and ceramic structures for ballistic protection via interference lithography coupled with infiltration into nanostructured templates. Such structures are comprised of a low density set of beams and joints. The Thomas and Boyce team employs 2-D and 3-D interference lithography to design and create microtruss networks. There are many variables available to design new structures with new properties (e.g., the particular truss geometry, the choice of polymer photoresist, the crosslink density, or the addition of nanoparticles to create nanocomposite microtrusses). Deformation mechanisms characteristic to a nanoscale structure combined with a purposeful mechanical design suggest a pathway for creating new ultralight, mechanically tough structures.

Professors Paula Hammond (CE) and Gareth McKinley (ME) have explored families of tough, high-energy-absorbing polyurethane materials which retain sufficient elastomeric properties for applications in the fabric of close-fitting soldier's uniforms. Polyurethanes are multiblock copolymers with soft and hard segments that microphase separately into small nanoscale domains. Professors Hammond and McKinley have synthesized polyurethanes with both semicrystalline soft segments and semicrystalline hard segments. The goal is the creation of high modulus, moderate tensile strain elastomeric materials that can exhibit desirable mechanical properties such as enhanced cut, tear, and puncture resistance and resistance to fabric wear in conjunction with breathability, cooling properties, and light weight. Additional materials that may be formed from this system include superior lightweight energy-absorbing layers for helmets and other body protection gear that would protect the predominant area of the soldier's body (including extremities) from low- to moderate-strain rate impacts such as those from general field maneuvers, sharp objects, falling objects, and shrapnel.

Professors Christine Ortiz (MSE) and Mary Boyce are studying naturally occurring shell structures to develop insights for the design of energy-absorbing protective materials.

Team 2: Mechanically Active Materials and Devices

Team 2, under the leadership of Professor Tim Swager (Chemistry), is developing nanomaterials capable of mechanical actuation and dynamic stiffness. Mechanical actuators embedded as part of a soldier's uniform could permit transformation from a flexible and pliant material to a nonpliant, armor-like material, thus absorbing the impact force of bullets and blast waves. Soft switchable clothing could also be transformed into a reconfigurable cast that stabilizes an injury such as a broken leg.

Contracting materials could be made to apply direct pressure to a wound, function as a tourniquet, or even perform CPR when needed. Mechanical actuators might also be used as exomuscles to augment a soldier's physical strength or agility.

There are a number of methods for creating mechanically active materials. Professors Paula Hammond and Richard Schrock (Chemistry) work on a new class of high strain response piezoelectric materials that can exhibit the toughness and high strain characteristics usually associated with thermoplastic elastomer materials. Professors Caroline Ross (MSE) and Gerbrand Ceder (MSE) are focusing on materials that change reversibly from ferro- or ferrimagnetic states to antiferromagnetic (nonmagnetic) states depending on the chemical environment—for instance, pH or oxidation state. Professors Thomas, Ian Hunter (ME), and Tim Swager are working on nanostructured conducting polymers and polymer devices containing the functionality desired for high performance actuators. This functionality is enhanced by the small feature size inherent to the materials, enabling very large gains to be made in response speed and performance.

Team 3: Sensing and Remediation

Team 3 is performing basic research that ultimately will lead to technologies for highly sensitive detection of chemical and biological substances, to be developed in collaboration with the Army and industrial partners. The goal of the team's basic scientific and engineering research is the enhancement of a soldier's awareness of and protection from various hazardous substances, including chemical or biological agents, poisons, and other environmental toxins. In collaboration with other ISN teams, members of Team 3 are also developing protective fiber and fabric coatings that will neutralize or significantly decrease bacterial contaminants and other hazardous materials. Novel organic-inorganic hybrid nanocomposites, consisting of nanoparticles and formed using simple dip processing methods, will combine sensing and reactive components. Team 3 is also understanding the science that can provide ways to use infrared monitoring to detect the presence of chemical agents or other threats, based on hollow photonic band gap fibers or nanoparticle quantum dot systems. Team 3, led by Professor Hammond, represents collaborations across several departments, including Physics, Chemistry, CE, Electrical Engineering and Computer Science (EECS), MSE, and ME, and the Biotechnology Process Engineering Center.

Professors Alexander Klibanov (Chemistry) and Hammond have undertaken the goal of rendering virtually any item of military relevance permanently microbicidal using a process that is durable, nontoxic, and easy to apply by untrained personnel. Having previously made much progress toward creating bactericidal and fungicidal coatings, the focus during the past year has been on virucidal coatings, and specifically those lethal to influenza virus.

Exploring the potential of quantum dot technology, Professor Moungi Bawendi (Chemistry) and Professor Vladimir Bulovic (EECS) have continued work on the design and synthesis of optoelectronic devices for imaging and the detection of people and other objects.

Professor Hammond and Professor Angela Belcher (MSE) have published an article in the journal *Science* on their groundbreaking work on the viral synthesis of nanowires toward the application of biological self-assembly and biotemplating, with the ultimate goal of fabricating a self-powered biosensor which has higher sensing capability, resulting from the ordered nanostructure.

Professors John Joannopoulos (Physics) and Yoel Fink (MSE) have made great strides in their work with photonic bandgap fiber systems. They have succeeded in the demonstration of dynamic transverse all-optical tuning of resonant cavity modes in photonic bandgap fibers, the demonstration of thermal sensing fiber devices by multimaterial codrawing, and also designed and fabricated the first surface-emitting photonic bandgap fiber laser.

Team 4: Biomaterials and Nanodevices for Soldier Medical Technology

Team 4, led by Professor Neville Hogan (ME) and Dr. Kirby Vosburgh of MIT partner Center for Integration of Medicine and Innovative Technology (CIMIT), focuses on using nanotechnology to improve the detection and treatment of life-threatening injuries, such as hemorrhage, fracture, or infection. With new approaches to soldier triage and with automatic first aid, Team 4's goal is to begin recovery while the patient is still on the battlefield.

Of interest are battlesuit sensors that could relay details about a soldier's location and physical condition to headquarters. New nanosurfaces could detect biological and chemical agents and then protect the future soldier from those threats. Biomedical monitoring might use ultrasound to detect a hemorrhage in the injured soldier and then cauterize vessels to staunch the bleeding. Soldiers' uniforms could become exomuscular devices for medical applications, such as tourniquets and splints for broken bones. And new nanomaterials could instantaneously change their properties by electrical switching, thereby controlling the delivery and release of life-saving medications.

Specific examples of Team 4 research include work by Professor Bob Langer (CE) to develop novel surfaces that can change properties on demand, as well his work to exploit ultrasound to deliver medications harmlessly through nanoscale channels in the skin, or withdraw specimens of body fluids for bioassay, thus avoiding the need for and potential dangers of needles. Professor Greg Rutledge (CE) is investigating methods of growing artificial tissues such as cartilage, an especially challenging problem, by employing electrospun fiber scaffolds. Professor Michael Cima (MSE) is developing tiny devices that would allow for the on-demand administration of vasopressin for the prevention of hemorrhagic shock.

ISN's collaboration with CIMIT provides an essential connection to physicians and other scientists from the Massachusetts General Hospital, the Brigham and Women's Hospital, and other Boston-area medical centers to develop medical applications for ISN's new devices and materials. Civilian applications of exomuscular devices, for example, could include smart backboards, neck braces, splints, and casts, as well as active fabric tourniquets. Nanoscopic approaches to medical treatments will benefit civilians as well as enhance survivability of the future soldier. To identify opportunities for nanotechnology in combat casualty care, Team 4 leadership planned and held a workshop in November 2005, attended by representatives of the Army and leading Boston-area hospitals, on battlesuit medicine. The workshop identified hemorrhage and brain injury as good targets for nanotechnological intervention. Hemorrhage is a major cause of combat mortality. Brain injury is an especially challenging problem in combat medicine. The workshop identified early information on life-saving care (e.g., knowledge of the type, severity, and location of injuries, the determination of when medical intervention is appropriate and necessary, and how to properly treat injuries) as a key functionality for the battlesuit, and medical sensing as a key enabling technology.

Team 5: Processing and Characterization—The Nanofoundries

The mission of Team 5, under the leadership of Professors Greg Rutledge and Gareth McKinley, is to develop the scientific and engineering understanding needed to process nanoscale and nanoenabled building blocks into useful macroscale materials and devices. These include fibers and fibrous materials, 3-D structures, and nanoscale surface coatings. The goals of Team 5 include development of novel methods of fabrication to ensure and enhance the performance of new nanomaterials, fabrication and integration of hierarchically structured materials to achieve multiple and synergistic property combinations, and prototyping and facilitating the transfer of ISN technology to industrial partners.

Over the past years, Team 5 researchers have demonstrated the capability to produce superhydrophobic fabrics through a combination of block copolymer self-assembly and electrospun nanofiber formation. An initiated chemical vapor deposition process developed by this team was shown to impart exceptional surface properties to both electrospun and conventional fabrics; such properties include antimicrobial activity, water and oil repellency, electrical conductivity, and wave guiding. During the past year, research on initiated Chemical Vapor Deposition (iCVD) showed that a wide range of homopolymers can be conformally deposited in ultrathin coatings (nominally 100 nm) on surfaces. Fundamental experimental and mechanistic modeling studies confirmed that iCVD polymerization occurs at the surface of the material being coated and provided foundational understanding that was used to scale up the iCVD process from a 200 mm diameter batch system to a 300 mm wide semi-continuous roll-to-roll process.

Composite fibers reinforced with single- and multi-walled carbon nanotubes dispersed in a polycarbonate matrix were fabricated and shown to exhibit improved mechanical properties. Electrospun fibers reinforced with exfoliated clay particles were fabricated and shown to exhibit improved flame retardant and heat resistant behavior. Self-actuated folding of 3-D origami structures using bilayers of chromium on silicon nitride was demonstrated, and a working electrochemical storage device was fabricated by this technique.

Team 6: Modeling and Simulation of Materials and Processes

Led by Professor Gerbrand Ceder (MSE), Team 6 has as its primary goals the modeling, simulation, and prediction of nanoscale phenomena and macroscopic properties; the prediction and optimization of materials response; and the design of novel nanoassemblies to protect the soldier from a variety of adverse loading conditions.

Additional objectives include developing a fundamental understanding of the structure, property, and processing relationships in nanosystems, developing numerical simulation capability to design and engineer new nanomaterial systems. and developing 3-D constitutive models of soft tissue response in order to design materials to protect the human body from trauma. Some particular accomplishments are highlighted in the following paragraphs.

Professors Ceder and Nicola Marzari (MSE) have developed large-scale ab initio simulation methods to understand the mechanism by which nanoparticles derive their unusual behavior. In particular, Professor Marzari clarified the mechanism for actuation of electroactive thiophene-based polymers, and Professor Ceder's group designed a new material that has the hardness of a ceramic but may be able to absorb large amounts of energy through an unusual electronic mechanism.

Professor Martin Bazant (Mathematics) developed the mathematical approach to describe the pumping and mixing of electrolyte systems at very small length scales by induced-charge electro-osmosis (ICEO) pumping. His team is currently experimentally testing a novel method to pump fluids in nanochannels, based on his theoretical work on ICEO. Such microfluidic labs-on-a-chip would allow noninvasive analysis of tiny samples or single cells, would be portable, and would provide for rapid assay results.

Professors Simona Socrate (ME) and Raul Radovitzky (Aeronautics and Astronautics) are working on computational models to simulate the effects of blast and ballistic deformation of armor on the human body. Professor Socrate has developed a constitutive model for the mechanical behavior of woven fabrics, of importance for the rational design of clothing for ballistic protection.

Team 7: Systems Integration and Technology Transitioning

The overall objective of Team 7 is to illuminate and apply systems integration requirements for using nanotechnologies to protect soldiers. To provide the individual soldier with unprecedented survivability capabilities, ISN envisions a dynamic, multifunctional battlesuit that synergistically integrates diverse nano and other components within a lightweight, comfortable garment. This suit is expected to be a complex system of systems. Therefore, to be effective, the suit components must perform in harmony with one another, *and* the suit must interact synchronously with at least two other complex systems—the soldier's body, and the soldier's operating environment. Team 7 seeks the understanding to enable these systems to work together and not at cross purposes.

Under the leadership of Professor Thomas and Dr. Bill Peters, executive director of ISN, Team 7 defined the following long range objectives:

- Develop scientific and engineering understanding to integrate different nanomaterials and nanodevices to provide multiple survivability capabilities in macroscale platforms

- Derive and improve this understanding through the design, construction, and experimental testing of simple prototypes that contain at least two nanoengineered building blocks
- Draw inspiration for battlesuit design and operation from other complex systems for life protection; e.g., the human body, extravehicle space suits, and desert mammals
- Formulate design tools and open systems architectures to integrate multiple, nanoenabled survivability capabilities in a battlesuit
- Use battlesuit systems architectures to illuminate needs in basic research, applied research, and transitioning

During the past year, Team 7 research concentrated on quantifying evaporative cooling of surfaces by nanoengineered membranes with straight-through pores. Such structures are also of interest for providing high mechanical strength in lightweight materials. Two different membranes gave appreciable cooling under heating conditions relevant to desert soldiers, suggesting the potential to nanoengineer porous overlayers to integrate evaporative cooling with lightweight materials for ballistic or blast protection.

Industrial Collaboration

Industry partners are critical to ISN mission because of the need to turn laboratory innovations into real products and scale them up for affordable manufacture at needed throughputs. ISN Industry Consortium, launched in 2002 with founding partners Raytheon, DuPont, and CIMIT (an affiliate organization of Partners Healthcare), now consists of the following 13 corporate collaborators, including Japan Electron Optics Laboratory USA (JEOL), which joined in October 2005:

Founding Partners
- Raytheon
- DuPont
- Partners Healthcare

Major Industrial Members
- Dow Corning
- JEOL USA

Small Business Industrial Members
- Carbon Nanotechnologies
- Dendritic Nanotechnologies
- Nomadics
- Triton Systems
- Zyvex

Interested Industrial Participants
- W.L. Gore and Associates
- Honeywell
- Mine Safety Appliances

It is the intent of the Army to make funding available for competition on an annual basis to assist ISN industry partners in performing applied research and development to transition promising ISN basic research results toward practical products for the soldier.

Outreach

ISN continued to maintain a very busy visit schedule during FY2006, hosting more than 430 visitors ranging from Army, Marine Corps, and Navy personnel to representatives of industry, international scientists, West Point cadets, prospective MIT students, families of MIT undergraduates, schoolchildren, and members of the general public. Prominent visitors included General Peter Schoomaker, chief of staff of the US Army; Dr. Francis Harvey, secretary of the US Army; General (retired) Gordon Sullivan, past chief of staff of the US Army and current president of the Association of the US Army; and Mr. John Young, director, Defense Research and Engineering of the US Department of Defense (DOD) and principal advisor to the Secretary of Defense on technical matters. ISN was also honored to host a visit by Dr. Dana Mead, chairman of the MIT Corporation, in January 2006.

Members of the ISN community visited several Army and other DOD installations during the year, including Fort Benning, GA, the USMA at West Point, NY, and the Edgewood Chemical Biological Center in Edgewood, MD. ISN staff and researchers have also delivered technical presentations at a number of conferences throughout the year. In addition, Professor Thomas is a member of the National Academies' Board on Army Science and Technology and has attended a number of meetings of that body.

ISN Army Nanotechnology Seminars continued with eight speakers, including Dr. James Murday, executive secretary to the US National Science and Technology Council's Subcommittee on Nanometer Science Engineering and Technology; Mr. James Von Ehr, founder of Zyvex Corporation; Dr. David Tevault, chief of physical and chemical sciences in the Research and Technologies Directorate at the Edgewood Chemical Biological Center; and Professor Elisabeth Smela, assistant professor of mechanical engineering at the University of Maryland.

ISN participated in several MIT outreach initiatives, including Family Weekend, Campus Preview Weekend, Research Science Institute, MIT Enterprise Forum, and the MIT Museum's Family Adventures in Science and Technology program.

Soldier Design Competition

The MIT Soldier Design Competition continued into its third year. The objective of the competition is to provide an engineering design experience for undergraduates that will address real technology problems faced by modern soldiers and first responders. USMA cadets joined the competition during its second year, several participating as part of their capstone engineering design course and working on the same challenges as the MIT teams, and continued with great success in the third competition. Third-year challenges included a universal battery charger, a water purifier for remotely located soldiers, and a height and velocity sensor to ensure the safety of air-dropped equipment, among others. Participants could also propose their own challenge and responding invention in an open design category.

Approximately 45 teams from USMA and MIT began the competition in September 2005, and 12 teams participated in the final judging on March 1, 2006. Seven teams were awarded industrially funded cash prizes that totaled $17,000:

Raytheon Award ($5,000
Team: Radiant Flux
Team members: Chandan Das, Justin Holland, Adam Leeb, and Gary Long (MIT)
Invention: water purifier using ultraviolet light

L3 Communications Award of ($3,000)
Team: EVCO
Team members: Stephen Samouhos, Corey Fucetola, James Iabuz, and Kevin Mears (MIT)
Invention: vehicle-mounted water distillation unit

Boeing Award ($2,000)
Team: WaveMaster
Team members: Kyle Vogt, Jeremy Conrad, and Grant Jordan (MIT)
Invention: height and velocity sensor for cargo drops

Foster-Miller Award ($2,000)
Team: Safety Blast
Team members: Nick Tsui, Adam Mulliken, Joe Walish, Jacque Tio, and Phil Vogel (MIT)
Invention: improved polycarbonate for transparent armor systems

General Dynamics Award ($2,000)
Team: Battle Beacon
Team members: Matt Sherburne, Terrel Culp, and Colonel Barry Shoop (USMA)
Invention: in-line GPS system for radio communications devices

Lockheed Martin Award ($2,000)
Team: JoeProof
Team members: John McCaskey, Matt Wilcoxen, Jimmy Holloway, and Tom Cai (USMA)
Invention: enhanced breaching tool

Director's Award ($1,000)
Team: HydrAlert
Team members: Luis Alvarez, David Kaufman, Joshua Lake, and Irina Shklyar (MIT)
Invention: human hydration monitor

Competition participants own the intellectual property rights to their inventions and are encouraged to pursue patents and commercialization. To that end, several of teams from previous years have taken their inventions forward. The members of Team Grapefruit (now Xitome) are working on a second generation of their battery scavenger, with changes based on feedback by Army soldiers who tested the units. Team ATLAS, now ATLAS Devices, continues to improve on the design of their powered rope ascender. The Surreptiles (now RallyPoint), competitors from the first SDC competition, have received a Phase II Small Business Innovative Research award from the Army and their invention, a glove-based computer input device, has been incorporated into the Army's Future Force Warrior Program.

ISN plans to continue the Soldier Design Competition on an annual basis, with the 2006–2007 competition slated to kick off in September 2006.

Appointments and Visitors

During the past year, ISN has undergone several substantial changes in its administrative staff.
On July 1, 2006, Professor John D. Joannopoulos, Francis Wright Davis professor of physics, will become director of ISN, succeeding founding ISN director Professor Edwin L. Thomas. Professor Thomas became head of MSE in January 2006. He remains an active participant in ISN operations, as well as an important member of ISN faculty and leader of Teams 1 and 7.

Mr. Franklin E.W. Hadley, formerly outreach assistant, was promoted to director of outreach in April 2006.

Also during the past year, two staff members departed ISN, Ms. Eve Downing, director of outreach, and Ms. Joanne Maxwell, assistant director for facilities and administrative operations.

One new headquarters staff member was appointed. Mr. Marco Carega was hired as an administrative assistant in July 2005.

A number of visitors contributed to ISN activities over the past year. Dr. Alex Hsieh, from the Army Research Laboratory, continued working full time at ISN as a visiting scientist, as did Dr. Randal Hill from the Dow Corning Corporation. Professor Vladimir Tsukruk of Iowa State University and Professor Shlomo Margel of Bar-Ilan University in Israel completed their sabbatical visits during this time. Other visiting scientists included Professor Mark Dadmun from the University of Tennessee at Knoxville, Professor Avgeropoulos Apostolos of the University of Ioannina, Professor Kookheon Char from Seoul National University, and Dr. Thomas Allen Godfrey of the Natick Soldier Systems Center. Lieutenant Colonel William Garland from the Natick Soldier Systems Center became ISN's uniformed Army liaison officer in July 2005. He resumed this position in November 2005, upon return from deployment overseas.

Future Plans

ISN's mission remains extremely relevant to current national priorities, and it is expected that key research directions will continue and new research themes will be added. A significant realignment of ISN's research structure will begin following the contract renewal expected May 1, 2007. In this structure, the research will be organized into five strategic research areas (SRAs), each hosting specific research themes. There will be one or more research project per theme.

The planned SRAs are:

- Lightweight Multifunctional Nanostructured Fibers and Materials
- Battlesuit Medicine
- Blast and Ballistic Protection
- Chem/Bio Detection and Protection
- Nanosystems Integration

John D. Joannopoulos
Director
Francis Wright Davis Professor of Physics

More information about the Institute for Soldier Nanotechnologies can be found at http://web.mit.edu/isn/.