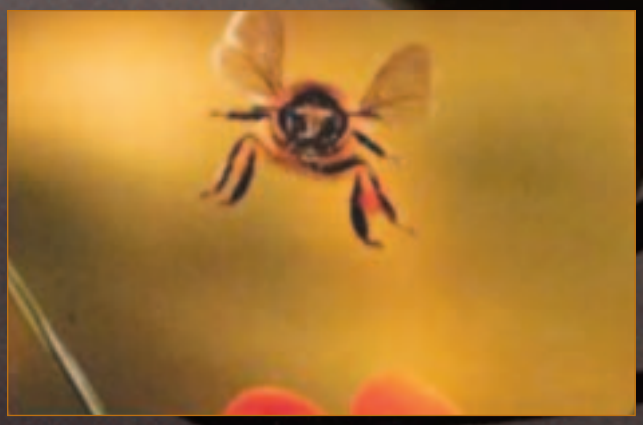
Smaller is definitely better! Micro-UAVs will help keep Soldiers out of harm's way and still enable them to gather information and track enemy movements — nearly undetected — on the battlefield. (Images courtesy of M.J. Tarascio and I. Chopra, University of Maryland.)

Army Basic Research — Creating Extraordinary Opportunities for a Capabilities-Based Army

Dr. John A. Parmentola and Irena D. Szkrybalo



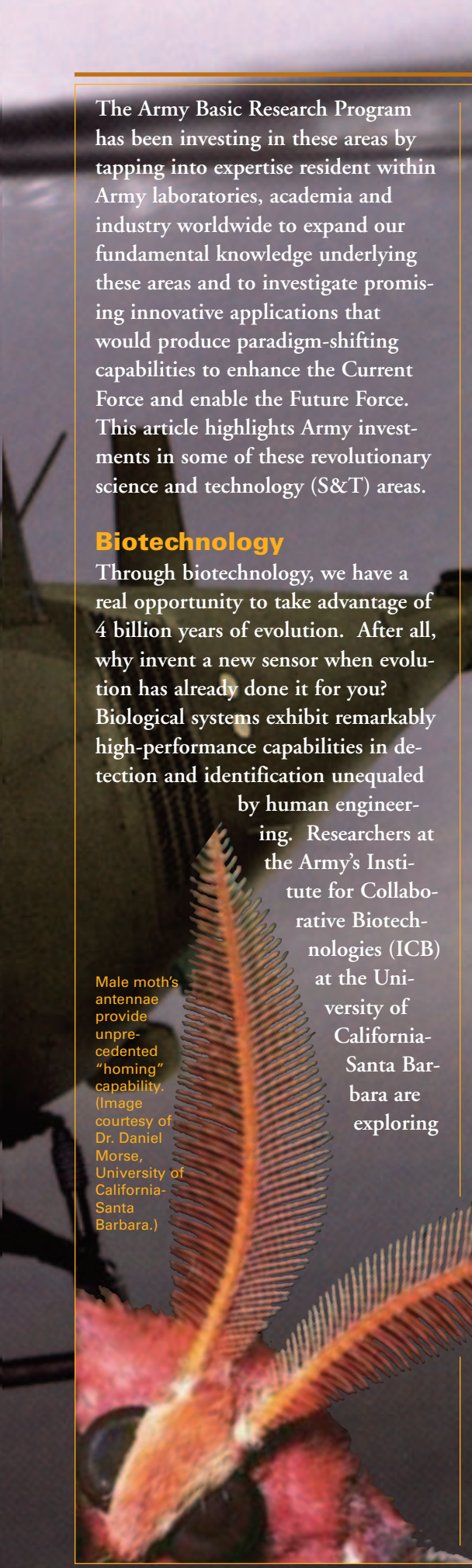
The flight of the bumblebee is helping scientists and researchers better understand navigational capabilities and advancements necessary to accommodate for instabilities and turbulence encountered by airframes in flight, particularly during take-offs and landings. (Image courtesy of M.V. Srinivansan, M. Poteser and K. Kral, Australian National University.)

The tragic events of 9/11 and our Nation's response to these horrifying acts of terrorism through the war in Afghanistan and the current conflict in Iraq are causing major changes to our national security strategy. DOD's *Quadrennial Defense Review (QDR)* process is addressing the current global security environment's challenges and is considering significant force changes. Exploitation of key technology areas such as advanced sensors, information processing, biotechnology, nanotechnology, cybertechnology and directed energy is being assessed within the *QDR* from the perspective of both U.S. capabilities and vulnerabilities.

The Army Basic Research Program has been investing in these areas by tapping into expertise resident within Army laboratories, academia and industry worldwide to expand our fundamental knowledge underlying these areas and to investigate promising innovative applications that would produce paradigm-shifting capabilities to enhance the Current Force and enable the Future Force. This article highlights Army investments in some of these revolutionary science and technology (S&T) areas.

Biotechnology

Through biotechnology, we have a real opportunity to take advantage of 4 billion years of evolution. After all, why invent a new sensor when evolution has already done it for you? Biological systems exhibit remarkably high-performance capabilities in detection and identification unequaled by human engineering. Researchers at the Army's Institute for Collaborative Biotechnologies (ICB) at the University of California-Santa Barbara are exploring the mechanisms of precision sensing found in nature. Through evolution, biological systems have evolved sensor capabilities that can detect chemical and other signals with sensitivity and specificity that are a million times greater than present man-made counterparts. As depicted below left, the chemical sensors in a male moth's antenna are capable of detecting a single female sex pheromone molecule, causing the male to home in on a mate from distances as much as a mile away — an excellent standoff capability.



Male moth's antennae provide unprecedented "homing" capability. (Image courtesy of Dr. Daniel Morse, University of California-Santa Barbara.)

The human eye can detect a single photon of light. ICB investigators, using tools of modern biotechnology, are dissecting these sensory systems to reveal the underlying secrets of these remarkable capabilities. They've discovered the two fundamental principles responsible for this high performance:

- In biological systems, signals received are amplified before being transferred to central processing systems.
- In biological sensory systems, the incoming and amplified information is transferred through the nervous system to a processor (i.e., the brain) through a series of molecular relay elements or transducers that fit together with a lock-and-key precision (mediated by molecular recognition) that has previously been unattainable through human technology efforts. The result is lossless transfer of information from antenna to the processor.

Researchers at the ICB are now translating sensory mechanisms into revolutionary new means of signal amplification and signal transduction to enable a new generation of sensors with greatly increased sensitivity and specificity. In a similar way, researchers at the ICB are working to develop lighter and more efficient portable systems for energy generation and storage for the Soldier. The quantum efficiency of photovoltaic generation performed during photosynthesis by every living plant on Earth is virtually 100 percent. In contrast, the best man-made solar energy converters today operate at approximately 10-20 percent. Again, using modern biotechnology tools, ICB investigators have dissected and revealed the underlying molecular mechanisms responsible for this remarkably high efficiency of energy generation, storage and use in biological systems. The principles discovered are being used to develop new materials for solar energy and lightweight batteries.

Biotechnology holds promise for the engineering and manufacturing of new materials for sensors and other electronic devices useful for ultra-rapid, ultra-smart information processing for use in targeting and threat avoidance. ICB's Dr. Angela Belcher has pioneered important breakthroughs by tapping into the biological self-assembly capabilities of phages (viruses that infect bacteria) to build highly precise, functioning electrical circuits with nanometer-scale dimensions. A nanometer is about 50,000 times smaller than the diameter of a human hair. By allowing genetically engineered phages to self-replicate within bacteria cultures over several generations, as depicted in the graphic on Page 46, Belcher has been able to identify and isolate those phages that are able to bind to particular semiconductor molecules with high affinity and high specificity. These phages can then self-assemble into a network on a substrate, forming exquisitely precise semiconductor arrays. The ultimate goal is to replace current suboptimal

electronic, magnetic and optical materials fabrication methods by genetically engineering microbes to build nanoscale circuits with exquisite nanoscale precision based on codes implanted in their DNA.

Using animals as detection devices isn't a new concept. The U.S. Army Medical Research and Materiel Command has developed a technique using common freshwater Bluegill sunfish to successfully monitor water quality in several towns across the country. Common Bluegill sunfish are wired with electrodes so their bodily functions can be precisely monitored on a computer display using signal processing algorithms for threshold detection in response to toxic chemicals in water. The system was used to successfully detect, in real time, a diesel-fuel spill from a leaking fuel line at a New York City reservoir. Fortunately, the reservoir intake was off-line at the time of the incident and no contaminated water reached consumers.

Similar activities that use living organisms as sensors are underway worldwide. The Belgian research organization, APOPO, has developed a potential solution to the detection of land mines using African giant pouched rats. In Tanzania, these rats have been trained to detect land mines with extraordinary high detection probabilities. Ongoing research is also being conducted using parasitic wasps to detect explosives, using rats as a fast and cheap detector for early diagnosis of pulmonary tuberculosis and using dogs to detect certain types of cancer in humans.

Nanotechnology

The Army is also pursuing novel approaches using nanomaterials for the warfighter ensemble to improve Soldier protection against ballistic projectiles, chemical and biological attacks, and enabling the ensemble to perform triage through the use of active control materials and diagnostic sensors. An immediate challenge is injury to Soldier extremities. The most prevalent battlefield injuries from *Operation Iraqi Freedom* include:

- Extremities (legs, arms, hands and feet), 62 percent.
- Head, neck and thorax, 24 percent.
- Abdomen and back, 13 percent.
- Other, 1 percent.

The Army Research Laboratory (ARL), in collaboration with the Army Center of Excellence in Materials at the University of Delaware, has developed a new garment based Kevlar® through the application of sheer thickening fluids to the material. These sheer thickening liquids are composed of nanoparticles of silica suspended in a liquid such as polyethylene glycol. When a high-speed projectile is injected into these liquids, the small nanoparticles are unable to get out of the way and are compressed into an essentially rigid mass that resists projectile penetration. At slow speeds, these nanoparticles are able to move around the projectile so there is little or no resistance to the incoming projectile. This has resulted in a version of Kevlar that is completely stab resistant while maintaining normal garment flexibility. The full potential of this new garment is being explored to assess its ability to limit certain types of extremity injuries to our Soldiers.

Recently, the Army's Institute for Soldier Nanotechnology at Massachusetts Institute of Technology (MIT) discovered a novel active control material dubbed exomuscle. This material has potential use as a prosthesis to aid Soldiers in handling and lifting heavy objects. Another potential application involves embedding this material into the Soldier ensemble along with physiological monitoring and diagnostic sensors so that the Soldier's uniform can act as a tourniquet to limit blood loss or to perform CPR when needed.

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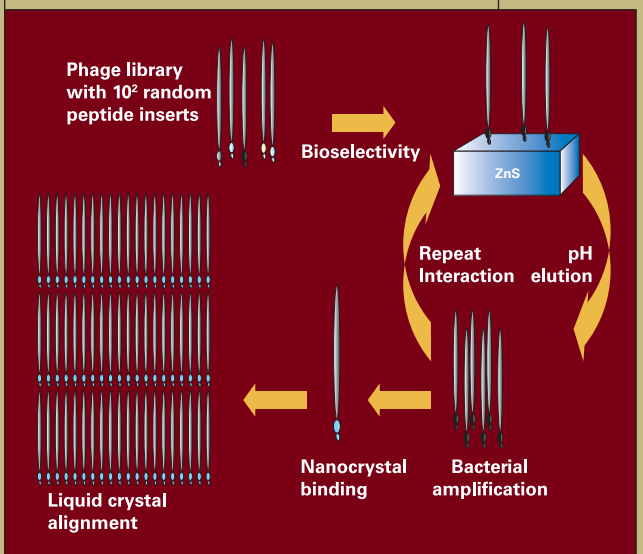

Scientists are attempting to use phages to genetically engineer microbes to build nanoscale circuits with exquisite nanoscale precision based on codes implanted in the microbes' DNA. (Image courtesy of Dr. Angela M. Belcher, MIT.)

We will also be embarking on the development of much smaller complex machines such as nanobots to perform microsurgery, to serve as prostheses to enhance Soldier capabilities, to enhance human physical endurance or to go into places that humans cannot. Nanoparticles can serve as encapsulating agents or platforms for hosting sensor and therapeutic biomolecules. Maintaining nanoparticles in circulation in the body, however, is a major challenge. Intravascularly injected nanoparticles are cleared from circulation within minutes by a system of cells found in the liver, spleen, lymph nodes and bone marrow that engulf and destroy bacteria, viruses and other foreign substances (phagocytosis). Red blood cells, however, can usually circulate for about 120 days before they are removed via phagocytosis in the liver and spleen. ICB is investigating mechanisms by which novel, long-circulating biodegradable nanoparticles can be used to adhere to red blood cells for prolonged periods of time for applications in continuous detection of metabolic markers, pathogenic threats or delivery of agents.

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Technology Trends

There are certain technology trends evident today that will persist well into this century. *Time compression* is one of these trends. For the Army, time compression applies to the conveyance of information at the speed of light but, more importantly, to the ubiquitous availability of high-performance computing (HPC) to process information very rapidly. These capabilities are key to situational awareness (SA) through knowledge management, data processing, data interpretation, information routing and link restoration, for network-centric warfare and Future Force operations. By embedding HPC capabilities into multisensor systems, execution of real-time multisensor data fusion processing will be possible, as well as high-confidence pattern recognition of images of ever-increasing complexity. This will also have very important

U.S. Army Soldiers from 2nd Battalion, 70th Armored Regiment, 1st Armor Division, patrol through Mamadia, Iraq, March 28, 2005, with soldiers from the 1st Presidential Iraqi Army. In the future, Soldiers will be able to disperse small, inexpensive sensors (Smart Dust, see inset) by the handful over operational areas to obtain information or maintain vigilance. (Photo by SPC Ronald Shaw Jr., 55th Signal Co. (Combat Camera); Smart Dust image courtesy of Dr. Kenneth Pister, University of California-Berkeley.)

Miniaturization will have a major impact on future operations, particularly in the area of flexible display technology for Soldier faceplates as depicted in the inset photo. (Inset image courtesy of Eric Forsythe and David Morton, ARL.)

consequences for achieving autonomous unmanned systems and reliable autonomous seekers for smart munitions.

Further advances in silicon-based HPC are likely to be overtaken by the rapidly developing area of 3-D molecular electronics and possibly DNA and *quantum computing* with speeds that will make our current supercomputers seem like ordinary pocket calculators. Famous inventor and futurist Dr. Ray Kurzweil has studied technology trends for the past 2 decades. He and his research team gather critical measures of technology in different areas and develop mathematical models of how technology evolves. He has concluded that genetics, nanotechnology and robotics will be the major paradigm-shifting technologies for this century. Kurzweil predicts a steady exponential progression in computing power, so that by the year 2050, our ability in computing will exceed that of all human brains — not just one, but all on the planet. Based on the Kurzweil prediction, the prospects are exceedingly good for achieving embedded HPC with remarkable speeds within the next decade.

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Another current trend is *miniaturization*. Space continues to be "compacted by the inclusion of more and more functions into smaller and smaller spaces. This will also have a major impact on time compression as well. On the horizon are golf-ball-sized systems with greater functionality to include advances in microelectronic-mechanical systems that will impact sensor systems, low-cost inertial navigation systems, diagnostics, prognostics and microcontrol systems, among others.

Logistics benefits will be realized by managing the real-time maintenance of warfighting systems on the battlefield through *predictive capabilities* involving sophisticated prognostic and diagnostic systems, all connected and communicating on mobile wireless networks. Further advances in miniaturization will also result in inexpensive self-contained disposable sensors, such as "Smart Dust" as indicated in the graphic on Page 47. Soldiers will be able to disperse these small, inexpensive sensors in handfuls over an area where they will self-organize and self-configure to suit the particular application.

Miniaturization will have a major impact on flexible display technology. The Army has taken the lead in this area through its newly formed Flexible Display Center at Arizona State University. Because flexible displays are conformal, they can be placed on a Soldier's faceplate or wrapped around a Soldier's arm. Within this decade, we expect to realize a wireless device contained within a 6- to 8-inch tube with a 1-inch diameter as indicated in the adjacent graphic. Given expected advances in miniaturization, computer memory, computational speed and speech recognition, researchers will develop compact devices with video recording, speech recognition, embedded mission rehearsal exercises, library storage, wireless communications and real-time SA through flexible displays — all in a compact form factor that will easily fit into a Soldier's pocket.

It is within our grasp to realize truly *"micro" unmanned aerial vehicles* (UAVs) that are human-hand-sized, or even smaller as depicted at the top of Page 44. These micro-UAVs will help keep our Soldiers out of harm's way while enabling them to gather information about various threats and to provide both lethal and nonlethal capabilities. We can take our inspiration for this system from the bumblebee as depicted on the bottom of Page 44. This small creature has a horizontal thrust five times its weight, is capable of 50-kilometer (km)-per-hour speeds with a 16-km range and has a body weight that is essentially 100-percent nectar (or payload).

Recently, we have been able to unravel the mystery of its navigation system — the bumblebee balances information flow from its left and right optical systems to navigate. Our current challenge is to understand the control system that enables this small creature to land precisely with zero velocity under modestly turbulent conditions. Achieving this capability will require extensive research in understanding small-scale instabilities at low Reynolds numbers, the development of lightweight durable materials and sophisticated control systems that work in turbulent environments. We must also learn how to develop active control materials that are highly efficient and low-noise propulsion systems with compact power and energy sources that can provide operational endurance.

ICT is pursuing innovative research of simulation technologies to create virtual immersive environments for Soldier and leadership training, mission planning and rehearsal in the safety of virtual reality.

Immersive Environments

A U.S. Army training objective is to exploit emerging technology and live, virtual and constructive simulation to offset the restrictions imposed upon live training, and use of high-technology weapons systems that result from safety considerations, environmental sensitivities and higher training costs. The Institute for Creative Technologies (ICT), located at the University of Southern California-Los Angeles, is pursuing innovative research of simulation technologies to create virtual immersive environments for Soldier and leadership training, mission planning and rehearsal in the safety of virtual reality. ICT is creating high-fidelity virtual humans, called avatars, to interact with people in an immersive virtual scenario. The avatars are synthesized using a wide range of software technologies such as speech recognition, artificial intelligence (AI), dialogue management, perception, animation and emotions. Simulated battlefield scenarios include the integration of a story line, filmed live action, computer-generated imagery and models. Soldiers learn by interacting with avatars that are able to adapt and learn in this dynamic immersive environment. ICT is leveraging the resources and talents of the entertainment and game development industries as well, and works collaboratively with computer, graphics, simulation and AI professionals to advance the state of immersive training and simulation technologies.

Army Educational Outreach Program (AEOP)

We won't achieve any of these marvelous things for our Soldiers without a highly capable future workforce that is well-versed in science, mathematics and engineering. An important strategic initiative in the Army S&T program is AEOP, which will help reverse trends that reveal a substantial erosion of our national prowess in science, mathematics and engineering. AEOP's goal is to increase the interest and involvement of U.S. students and teachers in science, math and engineering at all proficiency levels and backgrounds, including underrepresented and economically disadvantaged groups. In addition, AEOP is structured to provide sustained exposure of students and teachers to learning and teaching aids and to Army labs, scientists and engineers throughout their educational lifetime.

One such initiative is eCYBERMISSION, a fully Web-based science, math and technology national competition for 6th through 9th grade students. Established by the Army in 2002, 1,583 students participated in its first year, exceeding those of all other competitions of its kind in their first year. Currently, 6,886 students are participating, a greater than four-fold increase in just 3 years. A student team project by a 2003 eCYBERMISSION national winning team received the Presidential Environmental Youth Award presented by President George W. Bush at a White House ceremony April 22, 2004. The Army S&T program is committed to identifying, growing and developing future generations of Army scientists and engineers by instilling in our youth a fascination for the wonder and beauty of scientific knowledge and discovery.

DR. JOHN A. PARMENTOLA is Director for Research and Laboratory Management, Office of the Assistant Secretary of the Army for Acquisition, Logistics and Technology. He has a B.S. in physics from the Polytechnic Institute of Brooklyn and a Ph.D. in physics from MIT.

IRENA D. SZKRYBALO is a Senior Technology Advisor with Dynetics Inc. She has a B.S. in aeronautical engineering from Wayne State University and an M.S. in commercialization of science and technology from the University of Texas-Austin.