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There has been considerable discussion in the past decade of the Revolution in Military Affairs (RMA), one of those turning points in history where new technology and new ideas for its use in warfare have decisively changed the nature of military operations.[1] Stirrups, blitzkrieg, amphibious warfare, and other sharply demarcated advances in equipment and doctrine have given their inventors a significant advantage over less progressive opponents.[2] Discussion of the RMA has been driven by a belief that the United States is entering another such breakthrough, coupled with anxiety that some other power might surpass us or strike out in some new and unrecognized direction. Diligent search for the emerging RMA has become a small but well-funded industry in Washington.[3]

Although there is ritual acknowledgment that innovation could come from some unexpected direction, most debate centers on the application of information technology to conventional maneuver warfare. By wiring everything and everyone into a high-bandwidth information network, US forces of the future hope to achieve total "information dominance." Each tanker and pilot, and maybe each individual soldier, will know where all his own forces are on the battlefield, and where all the enemy forces are, day or night, in all weather. Naval battle groups will work as one integrated "system of systems" spread across a huge expanse of ocean, with an appropriate weapon able to respond to a threat detected by any sensor on sea, air, or space. Precision weapons will strike deep into enemy territory, based on excellent intelligence. Logistical systems will be much more efficient, delivering goods when and where they are needed with more precision and less overhead than today. And, above all, US forces will gain "OODA-loop dominance," being able to "observe, orient, decide, and act" much more quickly than our opponents. The official expression of this vision is in the JCS Chairman's 1996 document *Joint Vision 2010*, and it is elaborated in numerous publications by the military services and their supporting think tanks.[4]

There are other advances besides information technology in this standard vision of the RMA: exotic weaponry, including electric rail guns, lasers, radio frequency weapons, and other "directed energy weapons"; stealth technology applied to aircraft, ships, and even tanks and other ground systems; effective ballistic missile defenses operating from ground-, sea-, air-, and space-based platforms; unmanned vehicles to conduct reconnaissance and surveillance, ground attack, and perhaps even air superiority missions; and highly mobile forces able to deploy around the world on short notice, with greatly reduced logistics and less need for forward staging bases.

There is no doubt that much of this vision is technologically feasible, though perhaps not affordable, and that it would mark a great increase in our ability to prosecute military operations against a wide variety of foes. It is less clear, at least in this author's opinion, that it really constitutes a revolutionary change in the nature of warfare. To a great extent, the RMA merely represents the full maturation of operational concepts first developed in the 1930s and 1940s: mechanized warfare, air and ground coordination, three-dimensional naval combat, tactical command and control communications, elaborate systems for reconnaissance, surveillance, target acquisition, and intelligence collection, and so forth. Guderian and Patton would have recognized the American style of warfare in Desert Storm; Norman Schwarzkopf operated just like they would have, only faster and farther. It is likely they would be equally comfortable with the high-tech warfare of *Joint Vision 2010* and the Army After Next. Thus to find truly revolutionary possibilities for military operations--the RMA After Next--we must look beyond the questions of connectivity, mobility, and precision firepower that dominate the current discussion.

The Biotech Revolution

In a relatively short time, perhaps as soon as 10 to 15 years, we could be well into a technological transformation even more profound than the information revolution that is the focus of current attention. This transformation will be based on the convergence of information processing, biological sciences, and advanced manufacturing techniques. The result will be radically different approaches in the application of physical force against an enemy, as well as in the collection and processing of information.

The trend toward miniaturization is already well under way in numerous research projects, many funded by the Defense Advanced Research Projects Agency. At the extreme, some writers envision "fire ant warfare," with the battlefield dominated by millions of small semi-autonomous machines, a few inches to feet in size, networked together and capable of rendering an area impassable to troops or conventional mechanized formations.[5] Closer to the mainstream, researchers have built prototypes of small robotic devices to extend our reach on the battlefield: tiny unmanned aircraft, insect-like crawlers to carry sensors, and long-loiter high-altitude drones, for example.[6] It is taken for granted that such devices will be tied into our battlefield information networks, and that they will be inexpensive enough to be used on routine missions such as scouting in urban terrain.

As useful as these miniature devices are likely to be, they provide only a glimmer of what may be possible in the longer term. Rather than robots several inches in size, some ambitious researchers are talking about machines built atom by atom, measuring only a few nanometers (billionths of a meter) across. Such nanotechnology is in its infancy, but teams from Xerox, Cornell University, and IBM have demonstrated simple mechanical devices such as gears, wheels, strain gauges, electronic amplifiers, and even a working guitar built on the molecular scale.[7] (Put them together and you have the first bacterio-punk rock band--call them "E. Coli and the Slime Molds.") It may be decades before this research leads to useful nano-machinery, maybe much longer if one listens to critics who characterize the whole field as involving more showmanship than science.[8] But at a minimum, the research is producing remarkable advanced manufacturing techniques and molecular structural materials, and is likely to result in machines that are highly miniaturized if not actually microscopic.

Biotechnology has similarly been a topic of extensive interest, particularly in the wake of successful efforts to clone adult mammals. Much of the discussion has centered on therapeutic applications of genetic technology and on the ethics of procedures such as in-utero genetic testing, genetic intervention to "cure" conditions such as short stature, and human cloning.[9] What underlies all this hubbub are rapid advances in our understanding of how biological organisms function at the cellular and molecular level. It is likely that such progress will accelerate over coming decades, as advances in genetics, endocrinology, immunology, neurophysiology, and other subdisciplines build a more detailed and complex picture of how organisms really function.

What has received less attention is the likely confluence of all three of these trends--the synergistic merger of molecular biology, nanotechnology, and information technology, pointing to useful new directions in the design of mechanical devices. Let us look at various components of this possible merger.

Mechanical Design

Advances in molecular biology are not limited to genetic expression and immunology; some researchers are delving into the physical, mechanical processes by which living cells function. How meter-long neurons move signal molecules from one end to the other in a few milliseconds; how enzyme molecules rip apart the two halves of a DNA strand to permit cell reproduction; how bacteria propel themselves using structures that are only a few molecules in size; these are essentially mechanical questions, and Steven Block at Princeton is developing tools to measure and understand the processes involved.[10] In the case of neurons, for instance, the answer turns out to be a rail-like structure running from one end of the cell to the other, and another molecule that functions as a fast locomotive to haul the signal molecule along the rail at high speed and deliver it to the other end.

This field of molecular biomechanics points toward a different approach to nanotechnology. The "traditional" approach, if one can use that term in so futuristic a field, seeks to build molecular structures modeled on the wheels, gears, levers, and electronics of the everyday world. Some refer to this as "dry" nanotechnology, because it shuns the biological approach and the water-filled environment in which biological molecules function. It remains to be seen whether the dry approach will yield useful machines any time soon. The molecular-scale world is a whole new environment for designers, with many novel problems including quantum effects, thermal vibration, and chemical reactions with the surrounding environment. But "wet" nano-devices are the very fabric of life, and it is likely that molecular biology will be a fruitful source of proven successful designs, based on markedly different principles than the gears-and-levers approach of conventional mechanics.

Even in the design of normal-scale devices, greater understanding of biological systems will provide new approaches to movement, sensing, autonomous decisionmaking, and energy management. Making a robot that vibrates its whole exoskeleton to move its wings, like a dragonfly, or that flexes its body to swim like a lamprey, capitalizes on designs refined through millions of years of Darwinian trial and error.[11]

Energy Systems

In current efforts to build small, autonomous devices, one of the greatest obstacles is the energy supply. Chemical fuels are too heavy, photo-voltaic systems do not produce enough energy, especially in low light, and batteries either weigh too much, or don't produce enough energy for long enough, or both.

Again, molecular biology may come to the rescue, as machines shrink small enough to be powered by the same biochemical processes that sustain living organisms. It may be possible to harness photosynthesis or other biochemical energy mechanisms to fuel manmade devices.

Sensing and Information Processing

Prophets of nanotechnology, such as K. Eric Drexler and Ralph C. Merkle, talk confidently about building computational devices based on standard electronic circuit designs. Much effort has gone into devising nano-scale wires, transistors, and other building blocks of such a circuit.[12] Again, however, biology may offer different approaches to the computational problem. Study of neurological processes in simple multi-celled creatures such as worms, and more complex processes in higher creatures, helps to understand how biological entities process information, and is already giving rise to designs that mimic the procedures by which organisms perceive and react to their environment.[13] We are not going to replicate a bloodhound's nose any time soon, but studying how biological entities sense their environment, and how they use that information to find what they are looking for, is helping us design robotic devices that can search for mines or chemical agents, and move better over uneven terrain.[14]

The impressive information processing abilities of even tiny creatures may be useful in the miniaturization of ordinary computers. It is commonplace now to refer to DNA as information expressible as binary data, since it is a sequence of base pairs that can take one of four possible values. Richard Dawkins has gone so far as to assert that life itself can be defined as a self-replicating pattern of information that can evolve in response to its environment. Neal Stephenson takes Dawkins' argument further, asserting that there is no meaningful difference between DNA, computer viruses, language, religion, and fast food franchises--they all meet Dawkins' definition of life.[15]

Philosophical jousting aside, living cells must process a huge amount of data. In order for a cell to manufacture proteins, it must read data off the genetic code in its DNA. A human DNA molecule, like that of any complex creature, consists of about three billion base pairs arrayed along a molecule one billionth of a meter wide and nearly two meters long. So in effect, it is a data tape containing about six gigabits of data--750 megabytes--two billion times longer than it is wide. Every cell in the body contains a very efficient random access tape drive to spool the DNA up neatly, keep it from getting tangled, unwind and rewind it at high speed, find and read the appropriate genes for thousands of cell functions, and duplicate the entire tape accurately when the cell divides. Biologists at Cambridge University and the Swiss Federal Institute of Technology are gradually working out the mechanical functions of this tape drive, including the structure of its spools, how the spools wind and unwind, the nature of its copying machinery, and the role of the spools in activating or suppressing genes.[16]

The chemical and molecular mechanisms by which information is stored, moved, and processed in biological nervous systems may give rise to radically different designs for computational devices. We may be able to build devices that combine both electronic and biological information processing systems, thus gaining the advantages of both. A basic premise of modern computation, formulated by pioneering theorist Alan Turing, is that any computer can emulate any other, and neural network design currently seeks to replicate some of the functioning of animal brains. Emulation depends on fully understanding how the emulated system works, however, and we may be centuries away from that deep an understanding of biological cognition. In addition, there are often huge performance penalties inherent in the emulation process. But building in subsystems that actually incorporate, rather than emulate, neural systems may bring enormous improvements in pattern recognition, "fuzzy logic," environmental sensing, and other functions that living creatures perform much better than computers, without giving up the arithmetic and data-handling advantages and programmability of electronic systems. Researchers have taken tentative steps in this direction already; neurophysicist Jerome Pine and colleagues have integrated cells from rats' brains into silicon circuits, and a company called Affymetrix, affiliated with the Whitehead Institute at MIT, is embedding genetic material on the surface of silicon chips to quickly process and sequence DNA.[17]

Manufacturing

One of the great advantages of biological systems is that they "manufacture" themselves, given the right environmental conditions. Nanotechnology mavens argue with their critics over whether one can design self-replicating machinery, or even more ambitious, molecular "assemblers" that will use cheap, basic materials and software instructions to build machinery from molecular to starship sizes.[18]

Most discussion of manufacturing microelectromechanical devices focuses on the use of photolithographic techniques developed by the electronics industry.[19] This builds on mature technology, offering the advantage of high production volumes and low costs. Even more important, it allows the creation of both electronic and mechanical structures in one operation. Photolithography is probably not workable, however, if the device is designed around biomechanical components copied from nature. The most effective approach then likely would be genetic engineering and biological reproduction processes, such as currently used to induce bacteria or cloned sheep to make hormones and pharmaceuticals. A more distant goal is the merger of microelectromechanics and biomechanics, requiring a blend of these two radically different manufacturing techniques.

Military Implications

First, a dose of realism. It is easy to get carried away with such speculation. Even with rapid progress in all the necessary fields, it will be at least decades before we can mass-produce microscopic machinery tailored to our purposes. There is no reason to doubt that it is feasible in the long run, however, and some militarily useful products could be available in 20 years or so.

At a minimum, the merger of biotechnology, miniaturization, and information processing will produce machines that perform today's military tasks farther, faster, better, and maybe even cheaper. A more interesting question, however, is what new capabilities might derive from such devices, and how that might change the nature of warfare.

Novel Biological Warfare Weapons

Biological warfare heretofore has meant the release of infectious agents or biological toxins into a target population or agricultural area. Development has focused on selecting appropriate naturally occurring agents or toxins, growing them in large quantities, devising effective delivery mechanisms, and developing defenses against enemy biological warfare agents. As we understand more about how biological systems function, however, and learn to build machines or tailor microscopic biological entities to our specifications, the prospect arises that we can be much more specific and varied in our use of biological agents. Subject to prevailing law and arms treaties, of course, some possible applications include:

- Selective agents that can distinguish friend from foe through some biological or environmental criterion--genetic markers or chemical signals in the bloodstream, for example. If such agents were available, then preconditioning the battlefield or the actors would become an important phase of warfare--taking covert measures before the battle to make the foe more vulnerable, or friendly forces less vulnerable, and detecting or thwarting enemy efforts to do the same.

- Triggered agents that exert their harmful effect only in response to specific signals or circumstances, or that neutralize themselves on command.

- New ways to kill or incapacitate opponents. Programmable agents could be more carefully calibrated than the poisons and diseases of traditional biological warfare, and could exert whatever effect we could devise based on our understanding of how the body works at the molecular level--sleep, disorientation, paralysis, or disruption of the senses. Less subtle but equally effective would be mechanical effects, shredding key systems or organs from within.

- "Penetration aids"--agents tailored to bypass known defenses or immunities.

- Anti-materiel agents--bacteria that digest rubber, for example--but targeted on specific enemy systems or materials. Again, the combination of nano-computing and biological sensing systems should make it possible to make an agent that is much more selective in its action.

Radically Decentralized Sensor Nets

If miniature devices can process information, sense their environment, move, and communicate, they can form the fabric of a battlefield sensor network much finer and more decentralized than envisioned in conventional RMA scenarios. At the extreme, some predict the development of "surveillance dust," a cloud of millions of microscopic airborne sensors that could blanket a target area for extended periods to gather and report data.[20] Slightly less exotic is a "mesh" of thousands of small robots, several inches in size, that could be scattered across a battlefield to do both surveillance and attack functions, or clusters of orbiting microsatellites providing near-continuous ground coverage at relatively low cost.[21]

Again, the task of designing autonomous small devices that can sense their surroundings, move, communicate, and sustain themselves on energy and resources available in the ambient environment has already been accomplished; they're called bacteria and insects. Now we need to adapt the components of these successful designs to our specific needs.

Improved Processing of Sensor Data

Artificial intelligence researchers have sought for the last two decades to develop computer systems and software that mimic human processes for reasoning, pattern recognition, and processing of sensor data. Most of this research has been based on trying to understand mental functions from the "inside," as it were. That is, it tries to map out conscious and unconscious thought processes and emulate them in software or hardware.

Improvement in our understanding of the physical functioning of the brain, human or otherwise, offers an alternative approach to the same goal. To the extent that memory, sensory processing, and even cognition are found to be embedded in physical organization and chemical processes of the brain, we may be able to build biomechanical systems that emulate the structures and therefore the functions of natural brains. This should help in areas that have been resistant to standard artificial intelligence approaches, such as pattern recognition and the ability to reach a conclusion from incomplete information. At the extreme, it may be possible to incorporate living neuron networks into silicone-based computers, merging both approaches to information processing.

Radically Different Offensive Platforms

Martin Libicki has described a future battlefield impassable to large armored platforms, which are attacked and defeated by swarms of small networked robots.[22] Neal Stephenson extrapolates further, making the lethal systems microscopic in size.[23] Both seem to be at the extreme of what may be feasible in the near future, but they do point up the possibility of a battlefield dominated by offensive platforms sharply different from the armored vehicles employed for the past 80 years. There is considerable discussion today about attack versions of unmanned aerial vehicles, pilotless fighter jets, and brilliant mines to search out and kill submarines. It is a small step from there, at least conceptually, to fleets of small, relatively inexpensive robots to attack enemy ships or ground formations. If small, networked, unmanned platforms can be made to disable or defeat a tank, then the whole nature of maneuver warfare could change.

The addition of extreme miniaturization and biologically derived design features would make such robots even more effective. Energy systems, locomotion, sensors, autonomous decisionmaking, and even self-defense mechanisms could be adapted from biological systems to give the mechanical ants of "fire ant warfare" some of the advantages of their natural cousins.

More Complex Defensive Requirements

Defending against the systems described here may be much more difficult than using them in offensive operations. First off, the smaller they are, the harder they are to detect. Furthermore, it may be extremely difficult to determine the function of a network even if individual devices are seized and examined. There is already a major trend in sensor design toward relaxed performance tolerances of individual sensor elements to reduce manufacturing costs, with high resolution being achieved through central processing of information from a large number of dispersed elements.[24] A radically dispersed network of miniature or microscopic devices might be comprehensible only from the central node, it being impossible to determine the purpose or function of the network by examining individual elements. Even determining who was operating the network might be impossible, if we were in an ambiguous combat situation.

Having detected such a network, we would then need tools to attack and neutralize it. If it consists of thousands or millions of small autonomous elements, then the only effective counter might be a defensive network of similar complexity to track down and destroy the enemy's devices. The enemy's sensors or weapons could pervade the entire battlespace, perhaps including our own bloodstreams, opening up an entire new microscopic theater of combat. Whether microscopic or merely miniature, we still would need whole new types of defenses to screen out or destroy enemy devices and attack the network connecting them.

Other aspects of defense in a bio-tech age are equally daunting. If biological warfare agents can be made more selective, or triggered on command, then it behooves both sides to take action prior to conflict to make the opposing population more vulnerable or their own less so. This could become a major peacetime requirement, a constant struggle to detect and neutralize enemy efforts to precondition our population or to immunize its own population. Moreover, in traditional biological warfare, toxic and infectious agents are few in number and relatively unchanging in their makeup and effects. The new era of customized agents will require constant innovation, design changes, and fielding to keep ahead of all rivals.

Finally, there are the problems of evolution and unintended consequences. If devices are designed and manufactured by biological processes, it will be tempting to include reproductive ability in their design in order to minimize production costs and extend their useful life. Even if we refrain from this hazardous temptation, not everyone will. An entity that can reproduce itself will, inevitably, evolve to adapt to its environment. If we field an effective defense against bio-tech devices, some few will escape through some quirk in their makeup, and the survivors will reproduce. Like penicillin-resistant strains of tuberculosis, a new generation of devices will flourish, immune to whatever almost killed off their forebears. In addition, it will take us a long while to develop a thorough enough understanding of biological processes to predict all the ways a certain entity might interact with humans, other entities, or the environment. Long before we have that deep understanding, we will have enough superficial understanding to start mass-producing biomechanical devices. It is inevitable that there will be unexpected effects, some of them perhaps quite adverse. Like Dr. Frankenstein, we may need to defend ourselves against our own creatures.

Conclusion

As with many other aspects of advanced technology these days, cutting edge developments in these fields are coming from the commercial and academic sectors, rather than from military research and development. This reflects a defining feature of the 21st-century strategic landscape. In the Cold War, advanced military systems, and supporting capabilities such as satellite imagery, secure communications, cryptology, strategic transport, and large-scale logistics, were available only to wealthy nations. Since the Soviet military was well-trained and competent, national security became in large part a race to maintain the edge in military technology. We are moving into a different world now, where the hardware and support components of an advanced military force are for sale on the commercial market to anyone who can pay. So military superiority will depend less on having advanced weapons and systems, since any opponent might obtain comparable systems, and more on the organization, training, doctrine, and operational competence of the armed forces who apply that technology on the battlefield.

In the case of the "next RMA," the application of information technology to late-20th-century weapons and platforms, it seems unlikely that any other country will proceed as quickly as the United States is already moving. The networking of tanks, aircraft, supply ships, and everything else in the force requires a major effort in procurement and systems engineering, accompanied by an equally large effort to develop doctrine, tactics, techniques, and procedures to exploit these new capabilities. With the cost of US military procurement and military R&D both exceeding any other country's entire defense budget, even our most advanced allies have little hope of keeping pace with the digitization of the American force. The technology will continue to decline in price, of course, and others will eventually follow us into the information age, but at some distance behind.[25]

The RMA After Next, however, could be considerably different. The basic research may be extremely expensive, but the resulting design and manufacturing techniques could be much less expensive than the *JV 2010* "system of systems." It is a multibillion-dollar affair to build a fabrication plant for state-of-the-art semiconductors, but the mass production of appropriately designed biologically based devices might be as cheap as making penicillin--or growing cockroaches. There are huge conceptual hurdles to overcome, both in the design of the "system of fire ants" and in the development of radically different operational concepts for their employment on the battlefield. Unlike the *JV 2010* and Army After Next model of warfare, however, this is not an area where the United States has already made a major commitment and is surging ahead at superpower pace. With every middle-ranked military power focused on emulating, or thwarting, America's 21st-century vision of Desert Storm on steroids, no one is moving toward the biomechanical alternative, and in any case the technology will not be mature for ten years or longer. But as the technology develops, there will emerge an opportunity for some country's armed forces to strike out in a direction radically different from the prevailing paradigm of military operations, and develop capabilities that their opponents are unable to counter.

Given the rapid progress in all the relevant fields--biological science, advanced manufacturing, microelectromechanical systems, and information processing--it is virtually certain that industry will develop hybrid biomechanical devices for military purposes in the next few decades. There is no danger that anyone will surpass us in the basic technology; commercial and academic researchers in the United States will remain on the cutting edge in all these fields. The question for the military is whether we will also take the lead in new operational concepts for these technologies on the battlefield, or whether our commitment to one vision of futuristic warfare will blind us to the emergence of an equally effective, but radically different approach. Will we do it, or will someone else?

NOTES

1. On the origins of the RMA concept, see Benjamin S. Lambeth, "The Technology Revolution in Air Warfare," *Survival*, 39 (Spring 1997), 74. For a good overview of literature on the subject, see Stephen Metz and James Kievit, *Strategy and the Revolution in Military Affairs* (Carlisle Barracks, Pa.: US Army War College, Strategic Studies Institute, June 1995).

2. The development of stirrups in Central Asia permitted several new developments in mounted warfare. Mongol horsemen could sit securely with both hands free, permitting them to wield from horseback their short, hard-to-flex bows. Opponents found this marriage of mobility and firepower devastating. As the technology spread to western Europe, it also enabled the development of heavy cavalry. By anchoring the armored knight securely to his horse, the stirrup transmitted the full momentum of knight and galloping horse into the charge, achieving unprecedented shock effect. In both cases, however, it was the novel concepts for employing the technology, as much as the technology itself, that produced revolutionary military effect.

3. See for example Michael Pillsbury, ed., *Chinese Views of Future Warfare* (Washington: National Defense Univ. Press, 1996); Bates Gill and Lonnie Henley, *China and the Revolution in Military Affairs* (Carlisle Barracks, Pa.: US Army War College, Strategic Studies Institute, May 1996); Paul Dibb, "The Revolution in Military Affairs and Asian Security," *Survival*, 39 (Winter 1997-98), 93-116.

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8. Gary Stix, "Trends in Nanotechnology: Waiting for Breakthroughs," *Scientific American*, April 1996, pp. 94-99.

9. For the pessimistic view of the ethical challenges, see Jeremy Rifkin, *The Biotech Century: Harnessing the Gene and Remaking the World* (New York: Putnam, J. P. Tarcher, 1998).

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13. Nicholas Wade, "Dainty Worm Tells Secrets of the Human Genetic Code," *The New York Times*, 24 June 1997, p. C1; Jacobson.

14. Jacobson.

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25. Gill and Henley.

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