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How Small Is Too Small?

Technology into 2035

Paul E. Kladitis

Major, USAF

Air Command and Staff College

Wright Flyer Paper No. 46

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Foreword

It is with great pride that Air Command and Staff College presents another in a series of award-winning student research projects from our academic programs that reach nearly 11,000 students each year. As our series title indicates, we seek to promote the sort of imaginative, forward-looking thinking that inspired the earliest aviation pioneers, and we aim for publication projects which combine these characteristics with the sort of clear presentation that permits even the most technical topics to be readily understood. We sincerely hope what follows will stimulate thinking, invite debate, and further encourage today's air war fighters in their continuing search for new and better ways to perform their missions—now and in the future.

ANTHONY J. ROCK
Brigadier General, USAF
Commandant

Abstract

The Department of Defense (DOD) anticipates the realization of biomimetic bird and two-inch, insect-sized systems within the 2015–47 period. Although robot systems of one millimeter or smaller are not explicitly specified in current DOD and Air Force technology road maps, the technological aims towards this size can be clearly inferred from official documents. This research assesses the likelihood of, and barriers to, the realization of true microrobots and nanorobots (defined as submillimeter-sized robots of micro-meter and nanometer proportions, respectively) that can perform in military applications by 2035. This research finds that the realization of true microrobots for military applications by 2035 is unlikely, except for a single case of microrobots. Furthermore, the realization of true nanorobots for military applications by 2035 is even more unlikely. Technological advancements accrued through striving towards the goals of true microrobots and nanorobots are critical if the United States is to achieve a technological edge in more realizable-sized miniature robots for military application. Additionally, these technological advancements are critical for reducing the size and payload of other military systems, including satellites, aircraft, weapons, C4ISR (C4ISR concept of command, control, communications, computers, intelligence, surveillance, and reconnaissance), and portable sensors. Thus, regardless of the feasibility of submillimeter-sized robots by 2035, the United States still should sponsor research and development of both true microrobots and nanorobots.

Acknowledgments

I received some assistance from two special individuals. Joseph Mait, who works at the Army Research Laboratory, sent his paper on his department's efforts in small robots. From the Air Force Research Laboratory, Dr. Leslie S. Perkins sent her briefing regarding her group's microbiomimetic remotely piloted aircraft road map.

Introduction

23 JAN 2035, 0032Z—An imperceptible speck pierces the thick air and enters the adversary's war room located somewhere on the other side of the planet. In his dimly lit control room in the high desert of Nevada, Captain Bright cringes slightly as he pilots his lead system across the war room. "It's still unnerving to me," he remarks to his pal at the next terminal. "I'm two freakin' feet in front of the defense minister's face, and he can't even see me!" Bright perches his microrobot onto the defense minister's left epaulet and repositions it until the adversary's entire campaign plan is in full view. Imagery and audio data stream in for the J-2.

After two weeks of assessing the situation, adversary analysts finally determine that all of the command and control computers in the bunker malfunctioned from the same cause sometime between 0300 and 0320. It appears that the VCC [positive supply voltage] pins on each microprocessor chip were severed. It was as if small explosions occurred at each pin location.

The preceding fiction may soon become fact.

Problem Background and Significance

Current trends in Department of Defense (DOD) research, development, and acquisition of remotely piloted systems point towards an evolution in remotely piloted or autonomous vehicles to systems the size of insects or much smaller.[1] Both the DOD and the United States Air Force (USAF) technology road maps anticipate demonstration and operation of bird- and insect-sized systems capable of persistent intelligence, surveillance, and reconnaissance (ISR) and limited kinetic attack abilities by roughly 2015–47.[2] Specifically, the Air Force Research Laboratory (AFRL) goals are to demonstrate bird-sized systems by 2015 and insect-sized systems by 2030.[3] The AFRL's goals are to demonstrate robust palm-sized air- and ground-based systems by roughly 2018.[4]

The DOD presently uses *micro* to refer to small autonomous systems about the size of one to two feet, or bird sized.[5] The DOD uses *nano* to refer to small autonomous systems the size of a large insect (i.e., about two inches).[6] However, these systems should more appropriately be labeled *miniature* systems or robots. This paper deals with the concepts of *true* microrobot and nanorobot use for military applications. *True* means the robots embrace micrometer and nanometer proportions, respectively. Hence, a microrobot is herein defined as a robot of about one by 10^{-6} meters (one micrometer, one micron, or 1 μm) or a robot constructed from components of micron proportions. Therefore, a microrobot could range in size from 1 μm to a few millimeters (mm). However, this report limits future microrobot projections to no greater than 1 mm. The diameter of a human hair is approximately 100 μm, and the diameter of a human red blood cell is 7 μm. From the perspective of a macroworld observer, a land, aerial, or aquatic microrobot would appear at its largest as an ant, gnat, or plankton, respectively, and at its smallest, it would be invisible. A nanorobot is defined as a robot of about one by 10^{-9} meters (one nanometer or 1 nm) or a robot constructed from components of nanometer proportions. Therefore, a nanorobot could range in size from 1 nm to a few microns in length. The spacing between crystalline silicon atoms is 0.543 nm, and molecules are of nanometer size. From the perspective of a macroworld observer, a nanorobot would be invisible.

Although systems 1 mm or smaller are not explicitly specified in current DOD and USAF technology road maps, the technological aims towards this size are clearly implied. Additionally, even though this report focuses on true microrobots of less than 1 mm in size, some of the results of this research can be extended to the larger insect-sized microrobots because they will have to overcome some of the same technology barriers to be realized.

This report analyzes and assesses the likelihood that true microrobots and nanorobots that can perform in military applications will be developed by 2035. This report also identifies key technological barriers to that development. Additionally, it argues that the DOD should still sponsor research and development (R&D) of both microrobots and nanorobots, even if their realization by 2035 is unlikely. This sponsorship provides a critical catalyst for driving both the miniaturization and the integration of sensors, communication systems, propulsion systems, munitions, control systems, power supplies, and packaging for use in realizing larger insect-sized systems and other military systems.

Background on Current DOD Miniature Robots

Table 1 summarizes current DOD miniature robot characteristics. The USAF currently employs the Battlefield Air Targeting Micro Air Vehicle (BATMAV [also known as Wasp III]), a flying robot used for situational awareness and reconnaissance in special operations.[7] The Marine Corps and the US Navy also utilize the Wasp III.[8] Several hundred such vehicles currently reside in the DOD inventory.

Table1. Summary of current DOD miniature robot system characteristics

System	Domain	Control	Propulsion	Payload	Size & Weight	Endurance
BATMAV (Wasp III)	air, 50–500 feet operating altitude, 10k feet max altitude	autonomous or remote	fixed wing, propeller, battery powered	GPS/inertial navigation system navigation, autopilot, two high-resolution video cameras (front/side look), infrared (IR), L-band (1–2 Gigahertz) data link	12×16 in., 1 lb.	40 mph, 45 minutes
Tactical Mini-Unmanned Air Vehicle	same as above w/11k ft. max altitude	same as above	same as above	same as above except no IR	20×21 in., 1 lb.	50 mph, 25 minutes
Toughbot	ground	remote	wheeled, battery powered	two video cameras, audio sensor	6×8 in., 2.1 lb.	2 hours
Throwbot	ground	remote	same as above	one video camera	6×2.5 in., 12 oz.	2 hours

Source: Created by the author

The Army currently employs the Tactical Mini Unmanned Air Vehicle (TACMAV), which is similar to the BATMAV.[9] The

Army and the Marine Corps presently employ the "Toughbot," and they are developing the "Throwbot,"[10] wheeled ground robots used for clearing buildings and short-range reconnaissance. Fifty-one Toughbots are already fielded.

In the 2015–47 period, the DOD anticipates the demonstration of biomimetic miniature robots. *Biomimetic* implies the mimicking of movement and appearance of such biological organisms as birds or insects with flapping wings or as crawling ground creatures. Biomimetic operation enables more covert operations by allowing the robot to better blend into the expected natural environment.

The realization of the novel size of the miniature robots has been enabled by advances in microscale technologies mostly from the fields of microelectronics, microelectromechanical systems (MEMS), and materials science over the past 30 years. Additionally, insect-sized miniature robots suitable for military application should be achievable in the near future.

Background on Current Microrobots

Credible scientific research in microrobot and microrobot-enabling technology has been conducted since the late 1980s[11] (including early 1990s Defense Advanced Research Project Agency–sponsored research). To date, crude microbots and microrobot components intended for crawling, flying, and swimming have been demonstrated for potential use in close-quarters inspection and medical and micro-/nano-nanometer manipulation/assembly applications.[12] Most of the current microrobot systems range in size from one centimeter to a few millimeters in length, demonstrate only crude movement under pristine laboratory conditions, and lack any integrated electronic control circuitry, onboard power supplies, sensors, or communication systems. Figure 1 shows scanning electron micrograph and captured video images of a microrobot fabricated on a 4.5-mm-square-by-0.5-mm-thick silicon chip.[13] The microrobot demonstrated linear motion at 453 μm/minute using 96 polycrystalline silicon thermal actuator legs arranged in six groups that mimicked the motion of six-legged insects. The microrobot was externally powered through three thick tethered gold bond wires 25 μm thick with an electric power consumption of 0.9 watts (W).

Figure 2 shows a captured video image of a microrobot 15 mm long fabricated out of a silicon chip.[14] This microrobot demonstrated linear motion of several mm/minute using eight silicon-heated polymide joint actuator legs. The micro-robot was externally powered through three tethered gold bond wires 25 μm thick with an electric power consumption of 1.3 W.

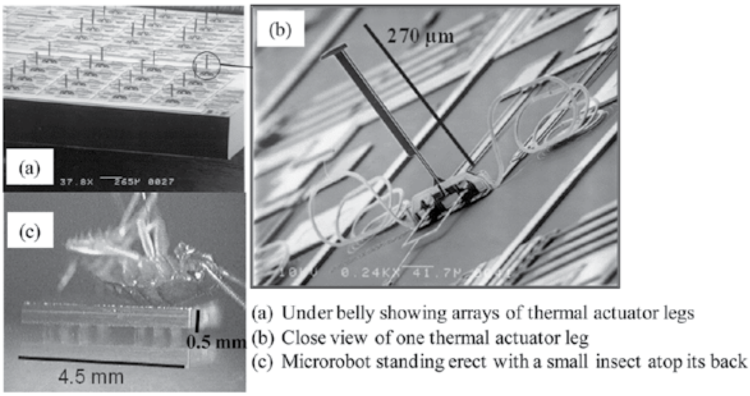

Figure 1. Scanning electron micrographs and video image of a 4.5×4.5×0.5 mm microrobot. (Reproduced from Paul E. Kladitis and Victor M. Bright, "Prototype Microrobots for Micro-Positioning and Micro-Unmanned Vehicles," *Sensors & Actuators A: Physical* 80, no. 2 [2000]: 132–37.)

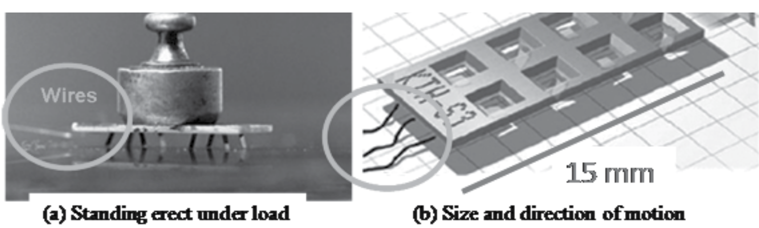

Figure 2. Captured video image and graphical depiction of a microrobot 15-mm long. (Reproduced by permission from Thorbjorn Ebefors et al., "A Robust Micro Conveyer Realized by Arrayed Polyimide Joint Actuators," *Journal of Micromechanics and Microengineering* 10, no. 3 [2000]: 337–49.)

A more integrated microrobot is that of Hollar et al., consisting of an integrated actuator foot, control circuitry, and solar cell. It should be able to demonstrate crude, uncontrolled linear movement about a few microns/minute with an electrical power consumption of 2.6 μW.[15] This microrobot is 8.6 mm in length. Figure 3 shows a captured video image of this integrated and autonomous microrobot.

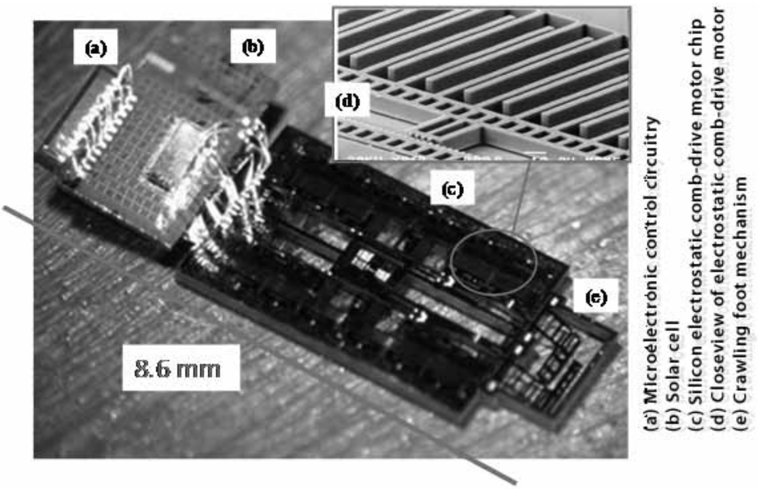

Figure 3. Captured video image of an integrated and autonomous microrobot. (Reproduced from Seth Hollar et al., "Robot Leg Motion in a Planarized-SOI, 2 Poly Process," *Proceedings of the Solid-State Sensor, Actuator, and Microsystems Workshop* [Hilton Head Island, SC, 2–6 June 2002], 54–58.); and, reproduced by permission from S. Hollar et al, "Solar Powered 10 mg Silicon Robot," MEMS 2003, Kyoto, Japan, 19-23 January 2003.

As shown in figure 4, the most advanced integrated and autonomous microrobot to date is the I-Swarm microrobot.[16] The I-Swarm microrobot is approximately 4 mm by 4 mm by 3 mm tall and consists of integrated solar cells used for power, light tracking, and reprogramming communication; an IR unit used for sensing and communicating with other I-Swarm microrobots; an application-specific integrated circuit used for overall control; three piezoelectric legs used for forward, reverse, and z-axis rotation movements; a piezoelectric touch sensor; and power storage capacitors. The I-Swarm components are integrated through a flexible printed circuit board. Locomotion is limited to operation on a flat sheet of 8.27×11.69-inch paper illuminated by a high-intensity lamp and an overhead image projection system used for programming the microrobots and displaying graphical navigation cues for the microrobots to follow.

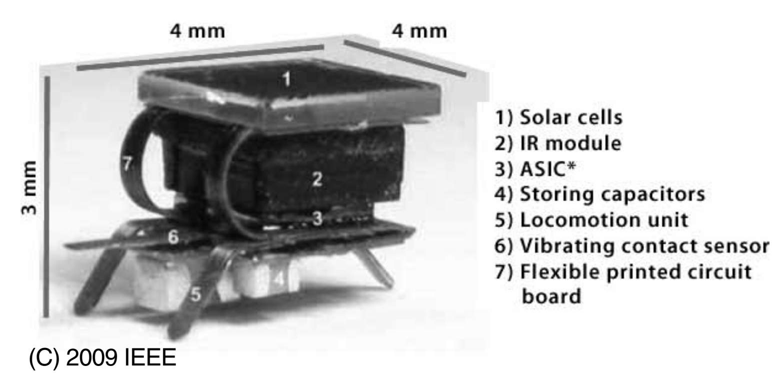

Figure 4. Captured video image of an I-Swarm microrobot. (Reproduced by permission from R. A. Casanova et al., "Integration of the Control Electronics for an mm^3-Sized Autonomous Microrobot into a Single Chip," *Proceedings of the 2009 IEEE International Conference on Robotics and Automation* [Kobe, Japan, May 2009], 121–27.)
*ASIC: application-specific integrated circuit.

In summary, the state of the art of microrobots is limited to sizes greater than 1 mm in length and to limited sensing and crawling operations in highly controlled laboratory environments. No integrated flying microrobots, at the scales discussed in this section, have been demonstrated. The micron scale of microrobot components has remained the same since their inception 30 years ago. What has advanced is the growing body of knowledge of microrobot construction and motion schemes, novel integration techniques, and microelectronics capabilities. It may take another 30 years of revolutionary breakthroughs to reach submillimeter-sized microrobots with robust autonomy, sensing abilities, and propulsion systems in real-world operational environments.

Background on Nanorobots

Nanorobotics is an emerging research field and can be generally divided into two areas: nanometer-scale manipulation of nanometer-sized objects and construction of nanometer-scale robots.[17] The first area, nanometer-scale manipulation, is already showing tangible results such as the manipulation of nanometer-sized particles using an atomic-force microscope tip or the manipulation of individual atoms using the electron beam of a scanning tunneling microscope.[18]

The second area, nanometer-scale robots, is only theoretical. Presently, the primary goal for nanorobots is that of an assembler, a self-replicating machine used to assemble materials or objects from the bottom up.[19] Most research in this area focuses on computer-aided modeling of such biological components as deoxyribonucleic acid (DNA) or proteins in hopes of someday harnessing their natural functions to perform nanoscale tasks. For example, Miki Hirabayashi and others propose using synthetically programmed DNA strands to realize various specific self-assembled DNA structures that can perform such specific tasks at the nanometer scale as communicating with bacteria.[20]

Nanorobots that have practical military application, like those proposed by K. Eric Drexler as "universal assemblers" with the ability to reorder atoms "with the precision of programmed machines," have not yet been demonstrated in any respect.[21] The most likely contribution in the near future of the larger field of nanotechnology will be the realization of nanoscale components (i.e., sensors, control circuitry, and power sources) used to help realize submillimeter-scale microrobots.

Future Concept of Operations

There presently exists no coherent work outlining concepts of operation (CONOPS) for using microrobots or nanorobots in military applications.[22] One notable contribution to microrobot CONOPS comes from a 1995 chief of staff of the Air Force–directed study of future capabilities required to ensure air and space dominance.[23] The study was performed by Air University through the Air Force Institute of Technology. Excerpts from the study follow:

> "Attack microbots" describes a class of highly miniaturized (one millimeter scale) electromechanical systems capable of being deployed en masse and performing individual or collective target attack. Various deployment approaches are possible, including dispersal as an aerosol, transportation by a larger platform, and full flying/crawling autonomy. Attack is accomplished by a variety of robotic effectors, electromagnetic measures, or energetic materials. Some "sensor microbot" capabilities are required for target acquisition and analysis. A "swarm" of 1 mm scale, flight-capable MEM(S) platforms provides unobtrusive, pervasive intervention into adversary environments and systems. Extremely small size provides high penetration capabilities and natural stealth.
>
> "Sensor microbots" describes a class of highly miniaturized (millimeter-sized) electromechanical air and ground systems capable of being deployed en masse to collect data, perform individual and collective data fusion, and communicate that data for further processing and distribution. Various deployment approaches are possible, including dispersal as an aerosol, transportation by a larger platform, and full-flying/crawling autonomy. Data collection is accomplished through miniaturized onboard sensors, typically restricted to one or two sensors per unit due to size and power limitations. Communications are possible by transmission through relay stations "relaybots" or physical collection of the microbots. Some applications of sensor microbots are security net to guard own assets, surveillance and reconnaissance, and intelligence gathering on adversary assets.[24]

Overall, the CONOPS presented below follow directly from a military interpretation of the aforementioned commercial microrobot applications of close-quarters inspection, medical, manipulation, and assembly discussed above. Additionally, concepts for microrobot CONOPS can be derived from miniature robot roles defined in the DOD *Unmanned Systems Integrated Road Map* and the *United States Air Force Unmanned Aircraft Systems Flight Plan*. These defined miniature robot roles are battlefield situational awareness, indoor or outdoor reconnaissance, surveillance, target recognition, sensing, lethal attack, irregular warfare, cyber attack, and swarming.[25] In essence, military microrobots will require capabilities similar to today's Global Hawks and Predators. The overall CONOPS will be presented in terms of a surface- or land-based mission scenario (microrobot and nanorobot operation in space and underwater domains is assumed to be impractical). Larger robots are assumed more suitable for space and underwater domains (e.g., space mines, directed energy offensive satellites, submarine remoras, etc.).

This report offers two novel sets of four futures scenarios CONOPS for microrobots and nanorobots, respectively. As shown in figure 5, *independent* implies each individual robot contains all the component functions necessary to conduct a mission alone, whereas *distributed* implies different component functions will be distributed among several robots to conduct a mission. *Remotely piloted* implies the robot will be remotely controlled during the entire mission, whereas *autonomous* implies the robot will perform independently, with possible limited remote control direction, throughout the mission. Each quadrant will dictate plausible robot technology requirements.

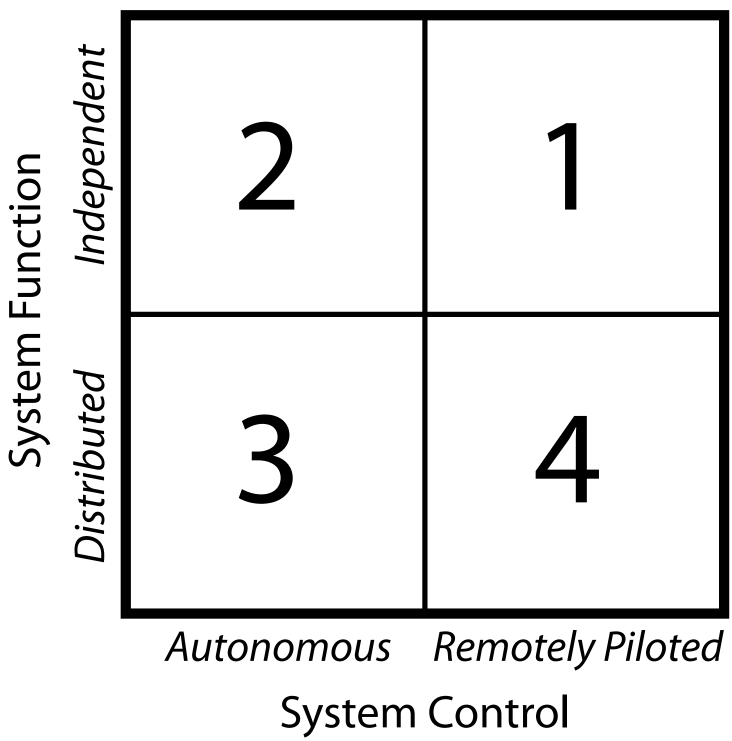

Figure 5. Four-quadrant futures scenarios CONOPSs for microrobots and nanorobots. (Created by the author)

Ingress of Quadrant 1 Robots: Independent and Remotely Piloted

Microrobots will be delivered (airdropped or ground released) to the general target area by a larger host such as a manned/remotely piloted vehicle, a kinetic projectile, or a human host.[26] Because of their small mass, microrobots will be highly survivable during such high accelerations and decelerations as those experienced by a tank or artillery shell. For example, such high-performance munitions as the 105-mm and the 120-mm armor-piercing, fin-stabilized discarding sabot (i.e., a device used in a firearm or cannon to fire a projectile) produce very high in-bore accelerations of 60,000 Gs, where 1 G is the acceleration due to gravity. Theoretical predictions for silicon microscale objects suggest survivability up to 136,000 Gs.[27] For microrobots to traverse relatively large distances to the general target area on their own will be as plausible and practical as that of such submillimeter biological organisms as gnats or fleas to perform the same feat. Therefore, it is unlikely microrobots will be able to traverse large distances to the general target area in a timely and reliable manner on their own. For microrobots relatively large distances will be defined by the endurance of their propulsion system and will be assumed in this CONOPS as any distance over a mile, with the exception of the ability to make course corrections during a high-altitude airdrop. Travel modes of crawling or swimming are assumed impractical and are discussed later in detail.

Once released from the host platform, an internal safe and arm mechanism will activate the microrobot. Depending on the mode of communication, the microrobots will be controlled from the host-delivery platform or some other nearby control or relay platform. Under remote control, the microrobots will fly to their final targets through caves, ducts, or cracks. During ingress to the final target, some of the microrobots may be positioned to set up a radio frequency (RF) or optical communication relay chain to communicate with the outside world. The establishment of a communication relay chain will be dependent on the magnitude of isolation of the final target operating area.

The number of microrobots the host platform delivers will depend on the specific mission and will include enough to establish a communication relay chain and perform the specific mission with redundancy. Controllers will have to use a remote control system suitable for maintaining control of several microrobots. Quadrant 1 microrobots will require some form of cooperative artificial intelligence to aid in the coordinated control of several microrobots. Nanorobots will not operate in this quadrant because of the expected limitations of their abilities due to their extremely small size.

Ingress of Quadrant 2 Robots: Independent and Autonomous

Ingress procedures for Quadrant 2 microrobots will be identical to Quadrant 1 microrobots except that they will fly to their final targets through caves, ducts, or cracks using a combination of predefined waypoints, target coordinates, and artificial intelligence. Just as moths home in on light and mosquitoes home in on heat, the artificial intelligence of microrobots will home in on various multispectral signatures while maneuvering around obstacles. Multispectral signatures would include electronic emissions, chemicals (e.g., biological or synthetic such as DNA, scents, explosives, fuels, etc.), sounds, light, images, or heat. The artificial intelligence of Quadrant 2 microrobots will also have to handle some form of cooperative behavior to aid in the coordinated movement of several microrobots.

Quadrant 2 microrobots may not require a communication relay chain during ingress unless their mission requires the transmission of data to or from an isolated operating area. Therefore, fewer microrobots may be delivered. Nanorobots will not operate in this quadrant because of the expected limitations of their abilities due to their extremely small size.

Ingress of Quadrant 3 Robots: Distributed and Autonomous

Ingress procedures for Quadrant 3 microrobots will be identical to those of Quadrant 2 microrobots. Depending on the specific mission, the number of microrobots will include enough to establish a communication relay chain (if required) and enough to perform the specific mission with distributed function and with redundancy.

Nanorobots will have Quadrant 3 capability. Due to their extremely small size, each nanorobot will possess only a singular capability; therefore, they are classified as distributed in function. Similarly, because of their nature and small size, they will not be remote controllable; nonetheless, they are also classified as autonomous in control. Quadrant 3 nanorobots will not have target homing and obstacle navigation abilities like Quadrants 2 and 3 microrobots. Nanorobots will have to be delivered precisely to their target by a larger host such as a microrobot, a larger manned/remotely piloted vehicle, or a human host.

Ingress of Quadrant 4 Robots: Distributed and Remotely Piloted

Ingress procedures for Quadrant 4 microrobots will be identical to Quadrant 1 microrobots. Depending on the specific mission, the number of microrobots will include enough to establish a communication relay chain and enough to perform the specific mission with distributed function with redundancy. Nanorobots will not operate in this quadrant because of the expected limitations of their abilities due to their extremely small size.

Mission of Quadrant 1 Robots: Independent and Remotely Piloted

Once microrobots reach their targets (e.g., open areas of enemy activity, command posts, offices, hideouts, computer/weaponry circuit boards, antennas, satellites, desks, and light fixtures perched atop an enemy soldier's hat or body part, etc.), they will be used to gather various multispectral (electronic signals, sound, images, chemical signatures, etc.) intelligence; reconnoiter; release individual or collective explosive charges, poisons, or corrosives; reprogram equipment; or sabotage with plausible deniability. Gathered data will not be stored for later retrieval but will be transmitted back to the control station in real or near-real time.

Microrobots will hover, reconnoiter, or find traverse stationary objects using their flying propulsion system. Motion such as crawling will be performed through small incremental movements using their flying propulsion system. Nanorobots will not operate in this quadrant because of the expected limitations of their abilities due to their extremely small size.

Mission of Quadrant 2 Robots: Independent and Autonomous

The mission of Quadrant 2 microrobots will be the same as that of Quadrant 1 microbots. An additional mission for Quadrant 2 microrobots may include passive monitoring. In this case, a propulsion system will not be necessary. These microrobots will be delivered during egress and will passively monitor the target area from wherever they have landed. Nanorobots will not operate in this quadrant because of the expected limitations of their abilities due to their extremely small size.

Mission of Quadrant 3 Robots: Distributed and Autonomous

The mission of Quadrant 3 microrobots will be the same as that of Quadrant 1 microrobots with the exception of distributed operation: one microrobot captures images; another, audio; a third, signals intelligence (SIGINT); and a fourth, kinetic effects. Alternatively, the collection of a single type of information may be distributed. For example, if the video resolution of a single microrobot is not sufficient to capture meaningful images alone, several microrobots may work to form a synchronized composite image similar in function to an insect's compound eye. Additionally, Quadrant 3 microrobots may also perform a propulsionless passive monitoring mission similar to that of Quadrant 2 microrobots.

Due to the nature of a nanorobot, the mission of Quadrant 3 nanorobots will probably be like a synthetic "virus" targeted against enemy materiel and, possibly, personnel. In essence, the mission of Quadrant 3 nanorobots will be a targeted chemical reaction. For example, nanorobots will render such enemy materiel as explosives and computer processors inert, reprogrammed, or reengineered.

Mission of Quadrant 4 Robots: Distributed and Remotely Piloted

The mission of Quadrant 4 microrobots will be the same as that of Quadrant 1 microrobots with the exception of distributed operation. Nanorobots will not operate in this quadrant because of the expected limitations of their abilities due to their extremely small size.

Egress

The egress procedures for all quadrant microrobots and nanorobots are the same. Microrobots and nanorobots will be considered expendable and will remain at the target area at the end of the mission. Reverse engineering or exploitation of a microrobot would be difficult but not impossible. An enemy analyst could observe the exterior construction of a microrobot using a high-powered optical microscope or scanning electron microscope. Furthermore, nondestructive inspection of the microrobot will be nearly impossible due to the packaging technique of the microrobot. However, an analyst could use a focused ion beam to cut the microrobot and then observe interior cross sections of the microrobot using transmission electron microscopy. Ultimately, if exploitation of a microrobot were a concern, the microrobot could self-destruct or dissolve via a dual-use reactive packaging medium. Due to the extremely small size of nanorobots, the collection and exploitation of nanorobots will be impractical.

Countermeasures

To counter microrobots and nanorobots, an adversary must deny their presence and their ability to communicate. A detection capability is impractical. Because of the robot's invisibility due to its small size, if an adversary were to try to monitor the electromagnetic spectrum for microrobot communication, the adversary would not know whether the detected signals were from some distant source or a robot. Ultimately, an adversary would have to resort to some broadband low-power jamming on-site to deny microrobots' ability to communicate. Jamming may be undesirable if it interferes with the adversary's own operations. Line-of-sight optical communication by microrobots would be nearly impossible to detect and deny. To deny the presence of microrobots about 1 mm or smaller, an adversary must operate in a clean-room or semiclean-room environment that utilizes carefully sealed enclosures with air duct filtration capable of blocking particles smaller than 1 mm in diameter. At a minimum, an adversary may have to construct enclosures meeting *US FED STD 209E **Class 100 or ***ISO 4 standards that statistically block particles greater than 5 μm in diameter. Ultimately, most adversaries may deem countermeasures against microrobots logistically impractical.

Logistics and Disposal

Microrobots and nanorobots will be mass produced and constructed as single expendable items. They will be stored in mission-tailored dispenser cartridges ready for loading on a host delivery platform. The robot-loaded mission dispenser cartridges will be stored in the clean and dry manner of conventional ammunition to prevent premature fouling or corrosion. The only maintenance required will be premission interrogation to confirm data links and microrobot system readiness. If an unacceptable number of microrobots failed, the dispenser cartridge will be discarded. Depending on the microrobot power source, microrobot sensor chemistry, and nanorobot composition, microrobots and nanorobots will have limited shelf lives. Unused microrobots and nanorobots will be incinerated.

*US FED STD 209E: Federal Standard 209E, "Airborne Particulate Cleanliness Classes in Cleanrooms and Clean Zones," General Services Administration, 11 September 1992.

**Class 100: Describes air with not more than 100 particles per cubic foot (of air). The particles are 0.5 microns and larger, and no particles are microns or larger.

***ISO 4: Describes air with not more than 83 particles per cubic meter (of air). The particles are one micron and larger, and no particles are five microns or larger.

Ethics

The public may perceive microrobots and nanorobots as chemical or biological weapons, especially if these weapons are used against personnel, and thereby consider them to violate certain principles of *jus in bello*.

However, microrobots are distinctly different from chemical or biological agents. Even though a microrobot could enter a human's body through the mouth, nose, or ears, a microbot is no more dangerous than if a human were to swallow a bullet or a radio. Nanorobots, however, will be constructed from a combination of natural or synthesized biological and chemical components. Depending on their specific mission, nanorobots may differ from chemical or biological agents only by their designed function; thus, legally, nanorobots may be classifiable as chemical or biological agents. A key consideration of the legal classification of microrobots and nanorobots may hinge on whether they are used against personnel.

Microrobot System Components

Figure 6 illustrates a relevance tree for the microrobots discussed in the CONOPS. To establish a maximum size-limit baseline for the required microrobot components, this

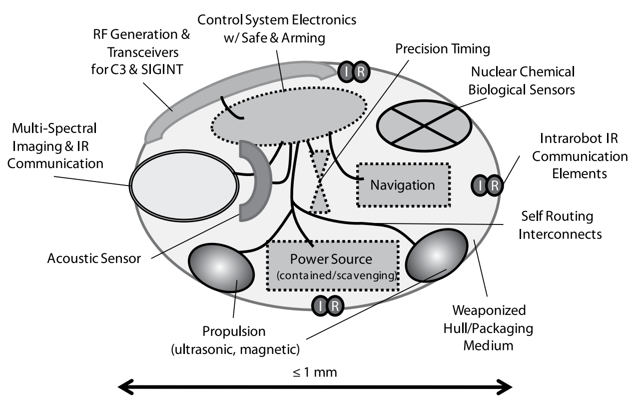

Figure 6. Graphical illustration of a microrobot relevance tree. (Created by the author)

report makes several assumptions about the size and number of components required to construct a microrobot suitable for military applications. First, a fabricated microrobot will probably not have a cube shape; however, for size estimation purposes, this report assumes a microrobot of one cubic millimeter (mm^3). Table 2 represents a tabular version of the relevance tree for each quadrant microrobot and includes allocated component quantities and volumes.

Table 2. Tabular microrobot relevance tree including allocated component volumes

	Quadrant 1 (Ind/RP)			Quadrant 2 (Ind/Aut)			Quadrant 3 (Dis/Aut)			Quadrant 4 (Dis/RP)		
Component	**Qty.**	**Add. CE**	**Vol. (mm^3)**	**Qty.**	**Add. CE**	**Vol. (mm^3)**	**Qty.**	**Add. CE**	**Vol. (mm^3)**	**Qty.**	**Add. CE**	**Vol. (mm^3)**
Control Electronics*	5.35		0.259	5.35		0.259	4.9		0.258	4.9		0.258
Nuclear Sensor Elements	0.3	0.15	0.015	0.3	0.15	0.015	0.3	0.15	0.016	0.3	0.15	0.016
Biological Sensor Elements	0.3	0.15	0.015	0.3	0.15	0.015	–	–	–	–	–	–
Chemical Sensor Elements	0.3	0.15	0.015	0.3	0.15	0.015	–	–	–	–	–	–
Optional TRX	2	1	0.097	2	1	0.097	2	1	0.105	2	1	0.105
Acoustic Sensor	0.3	0.15	0.015	0.3	0.15	0.015	–	–	–	–	–	–
RF TRX Elements	1	1	0.048	1	1	0.048	1	1	0.053	1	1	0.053
Timing Elements	1	0.25	0.048	1	0.25	0.048	1	0.25	0.053	1	0.25	0.053
Navigation System	1	1	0.048	1	1	0.048	1	1	0.053	1	1	0.053
Propulsion Elements	4	0.25	0.193	4	0.25	0.193	4	0.25	0.211	4	0.25	0.211
Munitions†	–	0	–	–	0	–	–	0	–	–	0	–
Power Elements	1	0.25	0.048	1	0.25	0.048	1	0.25		1	0.25	0.053
Integration Overhead (20%)			0.200			0.200			0.200			0.200
Totals	16.6	4.35	1.000	16.6	4.35	1.000	15.2	3.9	1.000	15.2	3.9	1.000

Source: Created by the author.

Legend: Qty. (quantity), Vol. (volume), RF (radio frequency), TRX (transceiver), Ind. (independent), RP (remotely piloted), Aut. (autonomous), Dis. (distributed), Add. CE (additional control electronics required for each component).

*Quantity equals one central control processor plus the total of the "Add. CE" column.

†Munitions are part of the microrobot packing material accounted for in integration overhead.

For each quadrant capability, table 2 lists the allocated quantity units (Qty.) for each component, the additional control electronics (Add. CE) required for each component, and the allocated volume (Vol.) for each component. The control electronics row reserves one control processor for a central control function plus the total of the additional control electronics column. The allocated volume for each component is calculated by dividing 1 mm^3 by the total number of allocated components in the Qty. column and then multiplying this by the allocated quantity unit for each component.

In estimating the allocated volume for each component, this report makes several subjective assumptions concerning the respective sizes of each component. For example, nuclear, biological, chemical, or acoustic sensor elements are allocated approximately one-third (0.3) the space of a navigation system component. Also, the additional control electronics allocations are subjective estimates. Furthermore, the absence of allocations for biological, chemical, or acoustic sensor elements in the Quadrants 3 and 4 columns is not intended to imply microrobots will not have these capabilities. Since Quadrants 3 and 4 microrobots have distributed function, they will have only a single sensing capability. This single sensing capability is symbolically allocated in the "Nuclear Sensor Elements" row.

Table 3 represents a relevance tree for a special case of a Quadrant 3 microrobot. This special-case Quadrant 3 microrobot is a passive, propulsionless robot that simply relays sensed information from wherever it is placed or lands. This special case represents a streamlined microrobot with the minimum number of components to accomplish a plausible, passive mission as described in the CONOPS. This microrobot may require either an optical or an RF communication system to relay sensed information (volume allocation is represented in "RF TRX Elements"), timing elements to synchronize data, a navigation system to geolocate data, and munitions as part of the integration overhead for self-destruction.

The primary significance of tables 2 and 3 is that the allocated component volume values will be used later to estimate the maximum component sizes required to realize 1 mm^3 microrobots by 2035. For example, a single control electronics processor unit or a power supply will have to fit in a volume of 0.048 mm^3 for Quadrants 1 or 2 microrobots, 0.053 mm^3 for Quadrants 3 or 4 microrobots, or 0.094 mm^3 for special-case Quadrant 3 microrobots to realize a microrobot of total volume 1 $mm.^3$ Equivalently, 5.35 control electronics processor units will have to fit in a volume of 0.259 mm^3 for Quadrants 1 or 2 microrobots. For simplicity this report assumes a maximum size limit for any single microrobot component of one whole volume unit. Table 4 summarizes these maximum component volume units.

Table 3. Special case, passive and propulsionless, Quadrant 3 microrobot relevance tree showing required number of components and volume allocation for each component

Component	Qty.	Add. CE	Vol. (mm^3)
Control Electronics*	3.5		0.329
Sensor Elements	1	0	0.094
Optical TRX Systems	0	0	0.000
RF TRX Elements	1	1	0.094
Timing Elements	1	0.25	0.094
Navigation System	1	1	0.094
Propulsion Elements	0	0	0.000
Munitions†	-	0	-
Power Elements	1	0.25	0.094
Integration Overhead (20%)			0.200
TOTAL	8.5	2.5	1.000

Source: Created by the author
Legend: Qty. (quantity), Vol. (volume), RF (radio frequency), TRX (transceiver), Add. CE (additional control electronics required for each component).
*Quantity equals one central control processor plus the total of the "Add. CE" column.
†Munitions are part of the microrobot packing material accounted for in integration overhead.

Table 4. Maximum microrobot component volumes

	Maximum Component Volume (mm^3)	Cube Length max volume$^{1/3}$ (mm)
Quadrants 1 & 2	0.048	0.363
Quadrants 3 & 4	0.053	0.376
Quadrant 3 Special Case	0.094	0.455

Source: Created by the author

Nanorobot System Description

The nanorobots will be constructed from synthesized or naturally occurring molecular biological components. They must be able to replicate or move in or beside the object where they are placed as they process their target material and either physically or chemically rearrange the molecules or atoms of the target material. The nanorobots will neither communicate nor collect data. They will simply react with their target material until their process has culminated or until their reaction has become limited.

Overcoming Technical Barriers

Control Electronics

State-of-the-art microprocessor electronic circuits are currently fabricated on crystalline silicon chips approximately 1 centimeter (cm) by 1 cm by 0.5 mm thick (thumbnail in size). The primary factor that determines the required size of electronic circuits and support systems, given a fixed transistor size and technology, is processing speed. Processing speed can be increased either by increasing the clock speed or by using parallel processing. Increasing the clock speed allows faster processing speed on a single chip or circuit, but it also requires more electrical power (e.g., 143 W for a high-performance processing unit with a heat sink), which in turn is dissipated in the form of heat. The heat is usually removed by a system of heat sinks and forced convection fans. However, the heat removal system can consume considerably more space than the microelectronic circuitry. Parallel processing is achieved by using redundant microelectronic circuits that break the processing down into several parallel tasks. In this manner, a microelectronic circuit can process information quickly, even with a slower clock speed, because the processing task is being performed in parallel. The drawback in terms of size for this method is the requirement for more chip surface area for the additional parallel processing circuitry.

Lower power-consuming microelectronic circuits are realized by decreasing the clock speed and reducing the power supply voltage. The reduction of power supply voltage is driven by several factors, especially reduction of transistor power consumption, reduced transistor channel length, and reliability of gate dielectrics. Current portable low-cost, hand-held, and uncooled battery-operated circuits presently consume approximately 3 W per 1 cm^2 chip.

Figure 7 provides a plot of projected electronics chip size. The curve in figure 7 extrapolates that in 2035, a 0.486-mm-by-0.486-mm electronics chip will hold the same number of transistors, with overhead, as a 1 cm^2 chip does today. This should indeed be plausible, since the 2035 chip size corresponds to a transistor (including overhead) density of 233,582 million transistors per cm^2, whereas the atomic surface density of crystalline silicon is 678,313,306 atoms per cm^2. Based on the microrobot maximum component volumes listed in table 4, this chip will meet Quadrants 1 and 2 volume restrictions as long as the substrate thickness is no greater than 0.048 mm^3 ÷ (0.486 mm x 0.486 mm) = 0.203 mm. Figure 8 shows the extrapolated power requirement for the 2035 chip of 0.007 W or 7 megawatts (mW). This power requirement will be used later in this section to estimate required microrobot power supply capacity.

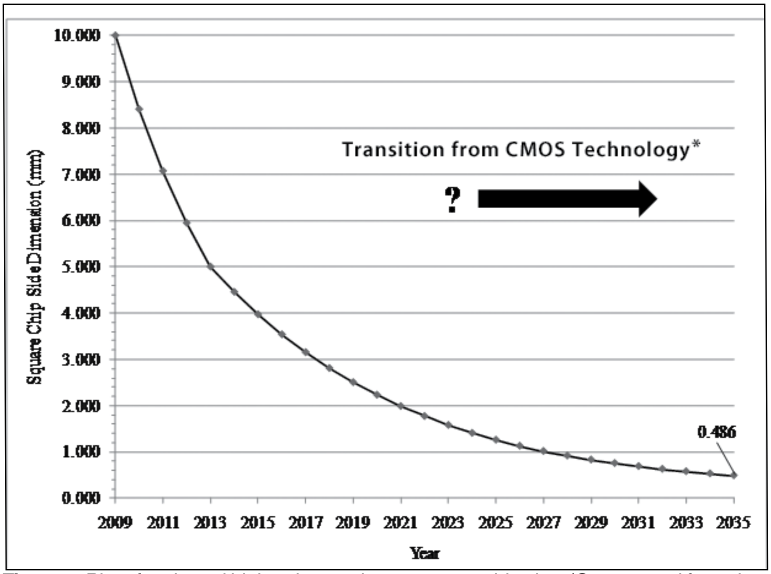

Figure 7. Plot of projected high-volume microprocessor chip size. (Constructed from data from International Technology Roadmap for Semiconductors, "The International Technology Roadmap for Semiconductors: 2009," 75, Table ORTC-2C. See the predicted number of transistors [including the logic core, memory, and interconnection overhead] per approximately 1 cm^2 high-volume microprocessor chip for the period 2009 to 2024. Data from 2025 to 2035 was extrapolated by curve fitting a fourth-order polynomial to the 2009 through 2024 data and extrapolating to 2035. The curve extra polates that in 2035, a 0.486-mm-by-0.486-mm electronics chip will hold the same number of transistors, with overhead, as a 1 cm^2 chip does today.)

*CMOS: complementary metal oxide semiconductor.

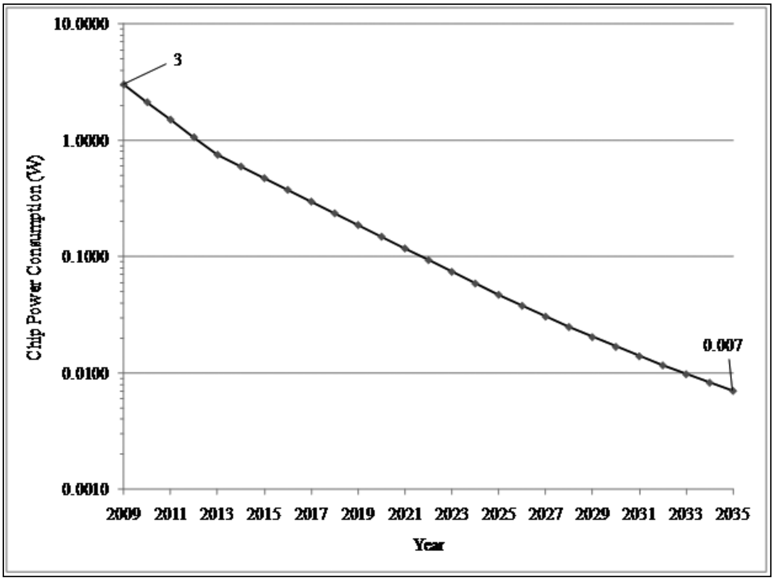

Figure 8. Plot of high-volume microprocessor chip power requirements corresponding to the decreasing chip sizes in figure 7. The curve shows that the extrapolated power requirement for the 2035 chip is 0.007 W or 7 mW. This plot was constructed from the data in figure 7 and assumes a target power consumption of 3 W, per low-power 1 cm^2 chip, is held as a design constant from 2009 to 2035. (Created by the author)

At some point, transistor technology will have to transit away from the current complementary metal oxide semiconductor (CMOS) technology to reach the target chip size by 2024 and, consequently, by 2035. Potential replacement technologies include carbon-based nanoelectronics, spin-based devices, ferromagnetic logic, atomic switches, and nanoelectromechanical system (NEMS) switches. Additionally, although the projected microprocessor size is on track to meet a single microrobot maximum component volume, the multiple microprocessor chips required to run a complete microrobot will have to be stacked together in some fashion to fit inside a microrobot. This will require a three-dimensional (3-D) integration technique yet to be realized.

In summary, current commercial electronics trends are on track to yield electronics suitable for incorporation into microrobots by 2035. However, the DOD may have to drive the transition from CMOS technology to keep pace with the current trend should the commercial sector choose not to. Additionally, the DOD may have to drive R&D in reliable 3-D circuit-stacking integration. This agrees with the National Research Council (NRC) Committee on Implications of Emerging Micro- and Nanotechnologies assessment that next-generation electronic devices such as scaled CMOS, single-electron transistors, spin-based electronics, molecular electronics, and carbon nanotube electronics may be available for application sometime within the next 10–40 years.[28]

Nuclear, Biological, and Chemical Sensors

Current commercial nuclear, biological, and chemical sensors are field-effect transistor or diode junction based.[29] Additionally, NEMS sensors based on resonating thin films and nanowires and optical-based nanoparticle systems are currently being developed.[30] The individual sensor element sizes, especially for transistor-based sensors, are already well under the microrobot maximum component volumes listed in table 4. Presently, these sensors are normally fabricated on relatively large substrates too large for microrobots. The only technical challenge for the future is in integrating these sensors on smaller substrates that will meet the microrobot maximum component volumes. This integration should be achievable by 2035. It agrees with the NRC's assessment that MEMS—or nanotechnology-based chemical and biological sensors—may be available for application sometime within the next 10 years.[31]

Multispectral Optical Components and Transceiver Elements

Current charge-coupled display (CCD) 640-by-480-pixel (0.5 megapixel) chips are approximately 2 mm by 2 mm by 0.5 mm thick. Complete digital microcamera systems including optical components, at present, are rarely smaller than 5 mm^3.[32] Decreasing the size of imaging systems may require such new paradigms as compound eye systems found in small biological organisms. These could be realized through microlenses and microlens arrays currently under development.[33] Additionally, the complete imaging system can be further miniaturized using other MEMS-based optical components with advanced packaging techniques also under development.[34]

Future microrobots may require high-resolution imaging to accomplish their mission. One way to realize this is to decrease the imaging pixel size. State-of-the-art imaging pixel sizes can range from 10 μm by 10 μm to 4 μm by 4 μm.[35] However, reducing the size of imaging pixels and associated optical components may encounter physical barriers due to the diffraction of light, since the visible light wavelengths range from 0.38 to 0.72 μm, and IR wavelengths of interest can range up to several hundred micrometers. If the microrobots were to operate in a distributed sense to achieve higher-resolution imaging where each robot represents a few pixels, the current absence of suitable miniaturized high-precision position and timing subsystems for composite image correlation and construction presents a technology barrier to microrobot-distributed imaging.

Adding the requirements of night vision, IR imaging, and transceivers for line-of-sight intramicrorobot communications further complicates the situation. Night vision requires miniaturized light amplification components. High-performance IR imaging requires miniaturized pixel-cooling subsystems unless a suitable miniaturized uncooled IR imaging system is realized by 2035. Optical components for millimeter-sized intramicrorobot communications have recently been developed. The I-SWARM microrobot uses a spatially arranged surface-emitting, light-emitting diode and photodetector line-of-sight, microrobot intracommunication subsystem that measures 3 mm by 3 mm by 1 mm thick.[36]

In summary, current state-of-the-art imaging systems do not meet microrobot maximum component volumes. Fortunately, R&D is headed in the right direction. Current commercial trends are driving the miniaturization of imaging systems for handheld devices and medical instruments. Furthermore, since imaging technology is closely related to standard integrated circuit technology, it may follow standard integrated circuit miniaturization trends to 2035. However, the DOD may have to drive R&D to reach submillimeter-sized high-resolution imaging systems, night-vision components, and uncooled IR imaging systems. Furthermore, the DOD may have to drive R&D of non-CCD/CMOS-based imaging pixels for both visual and uncooled IR imaging.

Acoustic Sensors

An example of a state-of-the-art microsized acoustic sensor is fabricated from piezoelectric thin films and measures 600 μm by 600 μm by 2.2 μm thick with a total volume of 0.0008 mm^3.[37] Since the size of this device is much less than microrobot maximum component volume requirements (0.048 mm^3), this device should be on track to complement microrobot systems by 2035. Reduction in thin-film width dimensions (under 600 μm), to be able to physically incorporate this into a microrobot while remaining sensitive to the 20 hertz–20 kilohertz audio range, could pose a technical challenge. However, this challenge can most likely be overcome by reducing the thickness of the sensing film appropriately. The primary technical challenge for the future is in integrating this sensor on substrates or with microelectronics that will meet the microrobot maximum component volumes. This possibility should also be achievable by 2035. It agrees with the NRC's assessment that MEMS- or nanotechnology-based multispectral sensors may be available for application sometime within the next decade.[38]

Multispectral RF Components and Transceiver Elements

Communication for remote control or intelligence and reconnaissance data telemetry via current RF system paradigms may be impractical due to physical barriers at this small scale regarding antenna efficiency, monolithic microwave integrated circuit (MMIC) size, and lack of transmission power to reach the outside world. For example, for efficient transmission, a dipole antenna should span a quarter of the respective RF communication wavelength. We can assume that a quarter wavelength antenna of 1 mm requires an RF communication frequency of 75 gigahertz (GHz) that is in the US industry standard W-band, international standard extremely high frequency band, or military standard M-band.[39] Development of W-band MMIC components and design techniques is currently under way. In terms of power requirements, assuming 0 dBi (decibel isotropic) gain microrobot transmit-and-receive antennas, 75 GHz, and a very good receive sensitivity of -120 dBm (decibel milliwatt) (very slow data transmission rate), microrobots could theoretically communicate at a distance of 2,500 feet (ft.) with 7 mW of available transmission power (same power estimated for a single integrated circuit processor chip in 2035), 1,000 ft. with 1 mW, and 30 ft. with 1 microwatt (μW).[40] Alternatively, assuming a higher data transmission rate with a receiver sensitivity of -80 dBm, microrobots could theoretically communicate at a distance of 30 ft. with 7 mW, 10 ft. with 1 mW, and four inches with 1 μW of available transmission power. Current state-of-the-art broadband SIGINT systems, including RF processing, amplifier, and filter components, are about one meter in size. It is highly unlikely that such a system can be reduced in size to meet microrobot maximum component volumes by 2035.

In summary, it is unlikely, given size and power constraints, that robust RF communication and sensing systems will be available by 2035 for practical microrobots without major technological breakthroughs. This evaluation roughly agrees with the NRC's assessment that certain MEMS-based RF sensor components may be available for application sometime within the next 10–40 years.[41] Furthermore, it is unclear whether MMIC technology will follow standard integrated circuit miniaturization trends to meet microrobot component-size constraints by 2035. One recent discovery using carbon nanotube resonators holds promise.[42] Nanotube resonators, a completely new paradigm in RF system design, may enable further miniaturization; however, adequate transmission power to communicate with the outside world still may be an issue, since this procedure seems to be independent of RF system technology. Finally, another recent discovery that may be used to overcome size and transmission power barriers is communication using quantum entanglement.[43]

Precision Timing

Miniaturization of rubidium- and cesium-based atomic clocks is currently an aggressive area of research.[44] Miniaturized atomic clock systems are about 1 cm in size and consume approximately 75–360 mW of power.[45] The current R&D paradigm consists of the direct miniaturization of large-scale atomic clocks based on the absorptive properties of rubidium and cesium vapor. The greatest technical challenge in atomic clock miniaturization is the miniaturization and packaging of the absorption cell (the "physics package"). It is unclear whether atomic clocks based on this paradigm can be further miniaturized to meet microrobot maximum component volumes by 2035. The DOD should drive R&D into further miniaturizing atomic clocks by two orders of magnitude more or find alternative paradigms in precision timekeeping.

Navigation Components

Current miniaturized inertial navigation systems are based on MEMS inertial elements, including accelerometers and gyroscopes. Inertial element grades are classified into three categories of increasing performance: tactical, navigation, and military. With few exceptions, most MEMS inertial components are tactical grade at best. However, tactical grade components may be suitable for the microrobot mission. For example, some of today's miniature military aerial systems and munitions take advantage of the Honeywell HG1930 MEMS inertial measurement unit, which is roughly two inches in diameter and 1.3 inches in height and which consumes less than 3W of power.[46] MEMS accelerometers and gyroscopes are electrostatically actuated resonating masses usually fabricated from silicon and are about the size of a few hundred micrometers in width and a few micrometers in thickness. Although each device is relatively small, the combination of three accelerometers, three gyroscopes, reference devices, control electronics, and other supporting components required to realize true navigation can become sizeable. Inertial element performance is a function of the mass of the element. The smaller the inertial element, the less sensitive it becomes. Therefore, a physical barrier exists to the further decrease in size of these elements.

In summary R&D is headed in the right direction in trying to miniaturize navigation systems. However, given the physical inertial barrier combined with the current size of MEMS-based navigation systems, it is unlikely that navigation systems based on the current MEMS paradigm can be further miniaturized to meet microrobot maximum component volumes by 2035. The DOD should drive R&D into further miniaturizing navigation systems based on alternative paradigms.

Propulsion

Even if all the aforementioned microrobot internal component technical barriers could be overcome by 2035, nature itself presents a significant exterior obstacle. The state of the art in microrobot propulsion is based on crawling, and this development will be impractical for several reasons, including the fractal lengthening of a surface's topology at the submillimeter scale, which could result in a never-ending journey through canyon-like crevices and around mazes of boulder-like particulates. Crawling microrobots could be knocked off-center by particulates or become entrapped in a quagmire of dust. A flying propulsion system will have to be powerful enough to enable the microrobot to withstand breezes, strong air currents, dust, and rain. The propulsion system will also have to be powerful enough to break the microrobot free from the surface tension of moist surfaces, small films of liquids, and the attraction of charged surfaces or environmental particulates. The propulsion system will have to reach relatively high velocities for the microrobot to travel to the target in a timely manner and achieve enough momentum to penetrate the aforementioned environmental conditions.

The DOD projects that the miniature, insect-sized "Nano-Flapping Air Reconnaissance Vehicle" will achieve technology readiness level (TRL) 6 by fiscal year 2013 with a less-than-two-inch wingspan and a maximum weight of 10 grams.[47] Theoretically, a 1-mm wingspan can provide enough lift to propel true microrobots.[48] However, it remains unclear whether actual microflight can be achieved in practice or whether it will be an effective form of propulsion for microrobots employed in a military mission. Most likely, a currently unknown method of propulsion may have to be discovered for true microrobots to surpass nature for military applications. One possible wingless method of flight propulsion may be found in acoustic streaming jets.[49] Additionally, due to the extremely small masses at the microscale, microscale objects effectively operate in microgravity conditions similar to operation in space. Therefore, another possible method of microflight propulsion could be one that takes advantage of the earth's magnetic field.[50]

In summary 30 years have transpired since the inception of the microrobot and microrobot propulsion components. To date only crude crawling and swimming of millimeter-scale robots in highly controlled laboratory environments have been demonstrated. Based on this trend, it may be another 30 years before robust microflight is realized. This assumption agrees with the NRC's assessment that MEMS-based propulsion may be available for application sometime within the next 10–40 years.[51]

Micromunitions

For microrobots to deliver appreciable kinetic effects to a target, new explosive materials must be found that pack a bigger punch into a smaller package. A possible material candidate currently under investigation includes nanoporous silicon that is reported to have more than doubled the energy output of Trinitrotoluene.[52] Other examples include metastable intermolecular composites, sol gels, and functionalized carbon nanotubes.[53] It is unknown whether materials like these will provide enough energy for microrobot mission accomplishment. Another possible munition could be a microsized nuclear weapon.

In summary and to the author's knowledge, no dedicated investigation into realizing microscopic explosive charges for application with microrobots currently exists. Additional research should further define microrobot target sets, associated required kinetic effects, and suitable energetic materials. It is unknown whether an effective explosive-laden microrobot is a feasible concept or will be available by 2035.

Power Supplies

Arguably, the most challenging area of miniaturization is in the ability to provide a long-endurance power supply for autonomous microrobots. Microrobots have been demonstrated to be powered or actuated using tethered wires, close-proximity inductive coupling of large coils, close-proximity capacitive coupling, vibration tables, thin-film batteries, close-coupled magnetic fields, pulsed laser beams, or solar power—all impractical for microrobot long-distance, autonomous operations.[54] Potential microrobot power supply schemes can be divided into two categories: self-contained or environment scavenging.

Examples of self-contained power supplies currently under development include fuel cells, turbine-powered electrostatic generation, and thin-film batteries that are all still too large or for some reason unable to provide enough sustainable energy for microrobots. One promising technology for self-contained long-term power generation is alpha- and beta-source radioactive decay, or nuclear batteries.[55] Another technology is a hybrid microscale MEMS fuel cell thin-film lithium (Li) ion source.[56]

An example will demonstrate the current inadequacy of self-contained power supplies for microrobots. First, consider a quadrant 1 or 2 microrobot that must provide power to the following major subsystems: control electronics, optical, RF, timing, navigation, and propulsion, altogether representing 14.35 components requiring power (table 2). Second, assume each of the 14.35 components requires the same power as a single microprocessor chip of 7 mW, for a total of approximately 100 mW of power required (14.35 x 7 mW = 100 mW). Third, assume the microrobot was powered by a thin-film Li ion battery that fits into the maximum microrobot component volume size of 0.048 mm^3 from table 4. Assuming a thin-film Li ion energy density of 200 watt-hour/kilogram (Whr/kg) and a Li compound density of 8×10^{-7} kg/mm^3, the battery can provide 7.68×10^{-6} Whr of power (200 Whr/kg x 8×10^{-7} kg/mm^3 x 0.048 mm^3 = 7.68×10^{-6} Whr). Therefore, the battery would be able to power the microrobot while all systems are functioning for 7.68×10^{-6} Whr / 0.1 W = 7.68×10^{-5} hours, or 0.3 seconds.

Examples of environment-scavenging power supplies currently under development include electromagnetic inductive coupling, electrostatic capacitive coupling, piezoelectric vibration, thermoelectric, pulsed laser, and photovoltaic.[57] Another example was demonstrated with silicone elastomer polydimethylsiloxane cantilever legs with rat cardiomyocyte heart cells cultured on their surfaces.[58] These microrobot legs demonstrated movement for up to two weeks while immersed in physiological liquids. These power source methods could provide indefinite power as long as they can be scaled down to fit within a microrobot and the microrobot can remain in the presence of the respective external stimuli or condition. Remaining within the external stimuli would prove impractical based on the microrobot CONOPS defined in this report.

In summary R&D is headed in the right direction in its search for long-endurance miniaturized power supplies. The DOD projects that "opportunistic power-grazing" technology for larger robot systems will achieve TRL 6 by 2031.[59] However, no suitable power supply for robust autonomous microrobots exists at present. Unless a significant technological breakthrough occurs soon, suitable power supplies for microrobots are unlikely by 2035. This timeline agrees with the NRC's assessment that MEMS-based power sources may be available for application sometime within the next 10–40 years.[60]

Integration: Assembly, Interconnection, and Packaging

For complete and robust microrobot systems to be realized, they need to be suitably mass-assembled from all of the aforementioned subsystems. One-by-one machine-assisted assembly will be impractical due to the large quantities of microrobots required. During microrobot fabrication, all microrobot components will have to be assembled into their proper relative positions, electrically or optically interconnected with each other, and suitably sealed together (packaged) to protect the internal components from environmental contamination, while at the same time providing suitable external interfaces for the optical transceivers, biological sensors, chemical sensors, acoustic sensors, and propulsion elements.

Most likely, due to their small size, microrobots will not be assembled using current machine-automated mass-manufacturing paradigms. One feasible mass-manufacturing technique is to fabricate thousands of copies of complete microrobot systems on a single substrate, deposit and pattern a final protective thin-film coating over each robot, and subdivide the substrate into individual robots. Currently, however, the aforementioned microrobot subsystems are fabricated using disparate technologies and materials. This condition will most likely persist into the near future. Therefore, any plausible manufacturing technique must accommodate the assembly of individual subsystems fabricated from disparate technologies. R&D has been poised for this inevitability, as evidenced in the investigation of micro and nano self-assembly techniques, which include the self-arrangement or positioning of microscale components by harnessing the surface tension of liquids, forces of magnetic and electric fields, adhesion of functionalized surfaces, strategically positioned microactuators, vibration, fluid-flow forces, centrifugal forces, shrinkage of polymers, and geometric matching.[61]

Assuming machine-automated micromanipulation technology will not be able to assemble complex 3-D arrangements and make intrasubsystem electrical connections required by the microrobots postulated herein, the following self-assembly paradigm is proposed. This paradigm assumes the microrobot-packaging medium will be engineered to facilitate three functions: assembly, interconnection, and weaponization. First, each individual microrobot component must incorporate the following additional design features: (1) chemically functionalized edges and/or surfaces, (2) an assembly facilitating geometry, (3) a packaging medium-phobic surface for those component surfaces that must face the exterior of the microrobot, and (4) self-routing electrical interconnection pads. Second, all required components for an individual microrobot will be injected into a droplet of the packaging medium. Once in the packaging medium droplet, the components will orient themselves with respect to each other via the attractive forces of the functionalized edges and surfaces, the repulsive forces of the packaging medium-phobic surfaces, and their assembly-facilitating geometries. Third, upon an external stimulus, the self-routing interconnection pads will form electrical pathways to their matching interconnect pads amongst the other components. The formation of the electrical pathways is facilitated by the packaging medium chemistry and is analogous to the growth of a biological nervous system. Ultimately, the packaging medium will cure, providing a hard encasing for the microrobot. The assembled microrobot will also be spheroidal in shape due to the surface tension of the liquid packaging medium before curing. The packaging medium will also serve as the explosive material for self-destruction or the delivery of kinetic effects. In the case that self-routing interconnects are not feasible, the self-routing interconnection pads could be replaced by tuned optical communication transceivers. In this case, the packaging medium must be engineered to provide total internal optical reflection so that the tuned optical transceivers on one component can communicate with matched sets on other components regardless of location. Additionally, in this case interconnections with the power supply must somehow be hard connected.

In summary current microassembly techniques are not able to assemble, interconnect, and package microrobots as postulated herein. It is unknown if this ability will be realized by 2035. The NRC's assessment is that some suitable assembly and packaging technologies may be available for application sometime within the next 10–40 years.[62]

Nanorobot Feasibility Evaluation

With respect to nanorobots, the same technical challenges that will plague microrobots will be magnified by several orders of magnitude. Additionally, due to physics at this scale, remote communication and information storage may be impossible.[63] Nanorobots will have to be employed exclusively and autonomously. Even if nanorobots were realizable, they will not be able to process their target material because the energy required to break and make atomic bonds will render atomic rearrangement unfeasible.[64] Furthermore, even if the atomic rearrangement function were realized, the time required for nanoscale objects to complete the macroscale sabotaging transformation of enemy materials would be impractical.[65] For these and a host of other practical physical limitations, the realization of nanorobots as postulated in this report may be unlikely regardless of period.

Summary and Conclusions

The current state of miniature DOD robots is represented by vehicles about a foot in size containing video and audio reconnaissance capability that can fly or roll on the ground with wheels. Additionally, the DOD goal is to realize biomimetic bird and two-inch, insect-sized systems within the

2015–47 period. The current state of complete microrobot systems is represented by robots about a half of a centimeter in size with crude crawling and limited serial optical communication capability in highly controlled laboratory environments. Furthermore, nanorobots are not close to being demonstrated. Table 5 summarizes feasibility assessments, and table 6 assesses the availability of microrobots and nanorobots by 2035.

Table 5. Summary of microrobot subsystem analysis and assessment

Microrobot Subsystem	Current R&D Vector	R&D Driven Commer-cially?	DOD Focused R&D Required?	Available by 2035?	Technology Break-through Required?
Control Electronics	Appropriate	Yes	Maybe	Likely	Yes
Nuclear Sensors	Appropriate	Yes	Maybe	Likely	No
Biological Sensors	Appropriate	Yes	Maybe	Likely	No
Chemical Sensors	Appropriate	Yes	Maybe	Likely	No
Optical Systems	Appropriate	Yes	Yes	Possible	Yes
Acoustic Sensors	Appropriate	Yes	No	Likely	No
RF Systems	Appropriate	Yes	Yes	Unlikely	Yes
Precision Timing	Appropriate	Yes	Yes	Unlikely	Yes
Navigation Systems	Appropriate	Yes	Yes	Unlikely	Yes
Propulsion	Appropriate	Maybe	Yes	Unlikely	Yes
Munitions	Needs focus	No	Yes	Unlikely	Yes
Power Supply	Appropriate	Yes	Yes	Unlikely	Yes
Integration	Appropriate	Yes	Yes	Unlikely	Yes

Source: Created by the author

Table 6. Assessment of the availability of microrobots and nanorobots by 2035

Robot System	Available by 2035?
Quadrant 1 Microrobots	Unlikely
Quadrant 2 Microrobots	Unlikely
Quadrant 3 Microrobots	Unlikely
Quadrant 4 Microrobots	Unlikely
Special Case Quadrant 3 Microrobots	Possible
Nanorobots	Unlikely

Source: Created by the author

Cutting-edge research is currently under way in miniaturized components and technologies required to construct true microrobots. However, key technical challenges and barriers exist in the further miniaturization of electronics, optical systems, RF systems, precision timing, navigation systems, propulsion, munitions, power supplies, and component integration, making realization of true microrobots by 2035 unlikely. Prospects for overcoming these challenges include next-generation electronic components, nanoresonator-based RF systems and sensors, quantum entanglement communication, acoustic streaming propulsion systems, nuclear or environment-scavenging power sources, self-routing nervous-system-like interconnects, and novel packaging/self-assembly mediums. One possible exception is the realization of special-case Quadrant 3 microrobots, passive propulsionless robots that simply relay sensed information from wherever they are placed or land. Special-case quadrant 3 microrobots are similar in concept to "smart dust" research that has been under way for the past several years.[66] The realization of nanorobots for military applications may be unlikely regardless of period. In fact, such present-day information operations core capabilities as electronic warfare and computer network operations are more practical for accomplishing the military missions envisioned for nanorobots.[67]

If technical challenges are not overcome, larger insect-sized robots may be the only practical choice for realization by 2035. However, technological advancements accrued by striving towards the goals of true micro and nanorobots are critical if the United States wishes to achieve a technological edge in more realizable-sized miniature robots for military application. Additionally, these technological advancements are critical for reducing the size and payload of a host of other military systems, including satellites; aircraft; weapons; command, control, communications, and computers ISR; and portable sensors. Thus, regardless of the feasibility of submillimeter-sized robots by 2035, the United States should continue to sponsor R&D of both true microrobots and nanorobots.

Notes

(All notes appear in shortened form. For full details, see the appropriate entry in the bibliography.)

1. Secretary of Defense, *Integrated Road Map*; and Secretary of the Air Force, *Flight Plan*, 2009–2047.
2. Secretary of Defense, *Integrated Road Map*, 165; and Secretary of the Air Force, *Flight Plan*, 2009–2047, 35.
3. Air Force Research Laboratory (AFRL), "Micro Air Vehicles," 1; and AFRL, *Science and Technology Strategy*, 22.
4. Mait, "Army Research Laboratory's Program," 3; and Mait, telephone interview by the author, 26 January 2010.
5. Secretary of the Air Force, *Flight Plan*, 2009–2047, 35; and Niles and Tran, "Study of Autonomous Micro-Robots," 1–22.
6. Secretary of the Air Force, *Flight Plan*, 2009–2047, 35.
7. Secretary of Defense, *Integrated Road Map*, 54.
8. Ibid., 81.
9. Ibid., 79.
10. Ibid., 132–33.
11. Trimmer, "Microrobots and Micromechanical Systems," 267–87.
12. Yeh, Kruglick, and Pister, "Microelectromechanical Components," 346–49; Ebefors et al., "Robust Micro Conveyer," 337–49; Shimoyama et al., "Simple Microflight Mechanism," 148–52; Fukada et al., "Micro Mobile Robot," 204–10; Gad-el-Hak, *MEMS Handbook*, 28-1–28-42; and Fatikow and Rembold, *Microsystem Technology and Microrobotics*, 303–65.
13. Kladitis and Bright, "Prototype Microrobots," 132–37.
14. Ebefors et al., "Robust Micro Conveyer Realized by Arrayed Polyimide Joint Actuators," 337–49.
15. Hollar et al., "Robot Leg Motion," 54–58.
16. Casanova et al., "Integration of the Control Electronics," 3007–12.
17. Weir, Sierra, and Jones, "Review of Research in the Field of Nanorobotics," 8.
18. Ibid., 15–29.
19. Hall, *Nanofuture*, 122.
20. Hirabayashi et al., "Toward Self-Assembly," 530–35.
21. Drexler, *Engines of Creation*, 14.
22. In the public domain and to this author's knowledge.
23. Jackson, Jones, and Lehmkuhl, "Operational Analysis," xii.
24. Ibid., 113, 128.
25. Secretary of Defense, *Integrated Road Map*, 17; and Secretary of the Air Force, *Flight Plan*, 2009–2047, 25, 34–35.
26. Solem, "Application of Microrobotics," 1.
27. Kladitis, "Materials for Harsh Environments."
28. National Research Council Committee, *Implications*, 8.
29. Son and Ziaie, "Implantable Wireless Microdosimeter," 256–59.
30. Cobianu et al, "Nano-Scale Resonant Sensors," 259–62.
31. Endo, Yanagida, and Hatsuzawa, "Optical Chemical Sensor," 947–50; and National Research Council Committee, *Implications*, 8.
32. Volkel, Eisner, and Weible, "Miniaturized Imaging Systems," 461–72.
33. Di, Lin, and Du, "Eyes Imaging System," 13–18.

34. Jung et al., “Miniaturized Camera System,” 819–23.
35. Itakura et al., “IT CCD Image Sensor,” 65–70.
36. Corradi et al., “Optical System,” 1–16.
37. Ren et al., “Micromachined Piezoelectric Acoustic Device,” 1–6.
38. National Research Council Committee, *Implications*, 8.
39. Calculated from $f = c / \lambda$.
40. Calculated using the Friis transmission equation $Pr = Pt\ Gt\ Gr\ (\lambda / 4\pi R)2$.
41. National Research Council Committee, *Implications*, 10.
42. Dragoman and Dragoman, “Tunneling Nanotube Radio,” 1–3.
43. Rosenfeld et al., “Atom-Photon Entanglement,” 1.
44. Wang, Lin, and Guo, “Micromachined Rb-85 Filter,” 911–14.
45. Stern, Stern, and Levy, “Nano-Atomic-Clock,” 1; and Kitching et al., “Power Dissipation,” 781–84.
46. Mohr and Fitzpatrick, “Navigation System,” 19–24.
47. Secretary of Defense, *Integrated Road Map*, 165.
48. Kubo, Shimoyama, and Miura, “Insect-Based Flying Microrobots,” 386–91; and Bronson et al., “Flapping Wings,” 1047–50.
49. Parviz et al., “Ultrasonic Electrostatic Resonators,” 586–89.
50. Johnson, “Tether Solution,” 38–43.
51. National Research Council Committee, *Implications*, 10.
52. Currano, Churaman, and Becker, “Nanoporous Silicon,” 2172–75.
53. Miziolek, “Nanoenergetics: An Emerging Technology Area of National Importance,” 43–48.
54. Gad-el-Hak, *MEMS Handbook*, 28–34.
55. Hassan and Faris, “Self-Reciprocating Cantilever,” 2758–62.
56. Chen, Vogt, and Rincón-Mora, “Design Methodology,” 674–77.
57. Chalasani and Conrad, “Energy Harvesting Sources for Embedded Systems,” 442–47.
58. Kim et al., “Cardiomyocytes,” 1405–8.
59. Secretary of Defense, *Integrated Road Map*, 168.
60. National Research Council Committee, *Implications*, 10.
61. Syms et al., “Self-Assembly of Microstructures,” 387–417; and Winkleman et al., “Templated Self-Assembly,” 900–910.
62. National Research Council Committee, *Implications*, 10.
63. Berube, *Nano-Hype*, 65–73.
64. Ibid.
65. Ibid.
66. Cook, Lanzisera, and Pister, “SoC Issues,” 117–96.
67. Joint Publication (JP) 3-13, *Information Operations*, II-4–II-5.

Abbreviations

AIT	automatic identification technology
ALCM	air-launched cruise missile
BCT	brigade combat team
BRIC	Brazil, Russia, India, and China
CAC	common access card
DOD	Department of Defense
EPC	electronic product code
ERS	expeditionary rescue squadron
ETSI	European Telecommunications Standard Institute
GAO	Government Accountability Office
GSEN	Global Supply Enterprise Network
HF	high frequency
IEC	International Electrotechnical Commission
IFF	identification, friend or foe
ISO	International Organization for Standardization
IT	information technology
IUID	item unique identification
LF	low frequency
MEMS	micro-electromechanical system
MICAP	mission capable
PICS	positive inventory control system
RF	radio frequency
RFID	radio frequency identification
UHF	ultra-high frequency
UID	unique item identification
USTRANSCOM	United States Transportation Command
VH	very high frequency

Bibliography

Air Force Research Laboratory. *AFRL Capability-Based Science and Technology Strategy 2030*, 31 July 2007.

———. "Micro Air Vehicles (MAV) Media Guide." Public Release, 88th Air Base Wing, October 2008.

Berube, David M. *Nano-Hype: The Truth behind the Nanotechnology Buzz*. Amherst, NY: Prometheus Books, 2006.

Bronson, J. R., J. S. Pulskamp, R. G. Polcawich, C. M. Kroninger, and E. D. Wetzel. "PZT MEMS-Actuated Flapping Wings for Insect-Inspired Robotics." In *Proceedings of the IEEE 22nd International Conference on Micro Electro Mechanical Systems—MEMS 2009*. Sorrento, Italy, 25–29 January 2009, 1047–50.

Casanova, R., A. Dieguez, A. Arbat, O. Alonso, A. Sanuy, J. Canals, J. Colomer, and J. Samitier. "Integration of the Control Electronics for an mm^3-sized Autonomous Microrobot into a Single Chip." In *Proceedings of the 2009 IEEE International Conference on Robotics and Automation*. Kobe, Japan. May 2009, 121–27.

Chalasani, Sravanthi, and James M. Conrad. "A Survey of Energy Harvesting Sources for Embedded Systems." In *Proceedings of the IEEE Southeastcon*. Huntsville, AL, 3–6 April 2008, 442–47.

Chen, Min, Justin P. Vogt, and Gabriel A. Rincón-Mora. "Design Methodology of a Hybrid Micro-Scale Fuel Cell-Thin-Film Lithium Ion Source." In *Proceedings of the 50th Midwest Symposium on Circuits and Systems-MWSCAS 2007*. Montreal, Quebec, 5–8 August 2007, 674–77.

Cobianu, Cornel, B. Serban, M. Mihaila, V. Dumitru, and F. A. Hassani. "Nano-Scale Resonant Sensors for Gas and Bio Detection: Expectations and Challenges." In *Proceedings of the International Semiconductor Conference*. Sinaia, Romania, 17 November 2009, 259–62.

Cook, B. W., S. Lanzisera, and K. S. J. Pister. "SoC Issues for RF Smart Dust." *Proceedings of the IEEE* 94, no. 6 (June 2006): 1177–96.

Corradi, P., O. Scholz, T. Knoll, A. Menciassi, and P. Dario. "An Optical System for Communication and Sensing in Millimetre-Sized Swarming Microrobots." *Journal of*

Micromechanics and Microengineering 19, no. 1 (2009): 1–16.

Currano, L., W. Churaman, and C. Becker. "Nanoporous Silicon as a Bulk Energetic Material." In *Proceedings of the International Solid-State Sensors, Actuators, and Microsystems Conference–Transducers, 21–25 June 2009*. Denver, CO, 2009, 2172–75.

Di, Si, Hui Lin, and Ruxu Du. "An Artificial Compound Eyes Imaging System Based on MEMS Technology." In *Proceedings of the 2009 IEEE International Conference on Robotics and Biomimetics*. Guilin, China, 19–23 December 2009, 13–18.

Dragoman, D., and M. Dragoman. "Tunneling Nanotube Radio." *Journal of Applied Physics* 104, no. 7 (October 2008): 1–3.

Drexler, K. Eric. *Engines of Creation*. New York: Anchor Books, 1986.

Ebefors, Thorbjorn, Johan Ulfstedt Mattsson, Edvard Kälvesten, and Goran Stemme. "A Robust Micro Conveyer Realized by Arrayed Polyimide Joint Actuators." *Journal of Micromechanics and Microengineering* 10, no. 3 (2000): 337–49.

Endo, Tatsuro, Yasuko Yanagida, and Takeshi Hatsuzawa. "Photonic Crystal Based Optical Chemical Sensor for Environmental Monitoring." In *Proceedings of the 7th IEEE International Conference on Nanotechnology*. Hong Kong, China, 2–5 August 2007, 947–50.

Fatikow, Sergej, and Ulrich Rembold. *Microsystem Technology and Microrobotics*. New York: Springer-Verlag Heidelberg, 1997.

Fukada, T., A. Kawamoto, F. Arai, and H. Matsuura. "Micro Mobile Robot in Fluid (1st Report, Mechanism, and Swimming Experiment of Micro Mobile Robot in Water)." *Transactions of the Japan Society of Mechanical Engineers*, Part C, 60, no. 569 (1994): 204–10.

Gad-el-Hak, Mohamed. *The MEMS Handbook*. Boca Raton, FL: CRC Press LLC, 2002.

Hall, J. Storrs. *Nanofuture: What's Next for Nanotechnology*. Amherst, NY: Prometheus Books, 2005.

Hassan, Mohamed H., and Waleed F. Faris. "Modeling of a Self-Reciprocating Cantilever for a MEMS Nuclear Battery Powered by an Alpha Source." In *Proceedings of the Inter-*

national Conference on Mechatronics and Automation–ICMA 2007. Harbin, Heilongjiang, China, 5–8 August 2007, 2758–62.

Hirabayashi, Miki, Kazuhiro Oiwa, Akio Nishikawa, Fumiaki Tanaka, and Masami Hagiya. "Toward Self-Assembly of Phage-Like Nanorobot." In *Proceedings of the 9th IEEE Conference on Nanotechnology IEEE-NANO 2009.* Genoa, Italy, 26–30 July 2009, 530–35.

Hollar, S., A. Flynn, C. Bellew, and K. S. J. Pister. "Solar Powered 10 mg Silicon Robot," MEMS 2003. Kyoto, Japan, 19–23 January 2003.

Hollar, Seth, Anita Flynn, Sarah Bergbreiter, and K. S. J. Pister. "Robot Leg Motion in a Planarized-SOI, 2 Poly Process." In *Proceedings of the Solid-State Sensor, Actuator, and Microsystems Workshop.* Hilton Head Island, SC, 2–6 June 2002, 54–58.

International Technology Roadmap for Semiconductors. "The International Technology Roadmap for Semiconductors: 2009." Accessed January 2010. http://www.itrs.net/Links/2009ITRS/Home2009.htm.

Itakura, Keijirou, Toshihide Nobusada, Noboru Kokusenya, Ryoichi Nagayoshi, and Masayoshi Ozaki. "A 1-mm 50 k-Pixel IT CCD Image Sensor for Miniature Camera System." *IEEE Transactions on Electron Devices* 47, no. 1 (January 2000): 65.

Jackson, Lt Col Jack A., Jr., Lt Col Brian L. Jones, and Maj Lee J. Lehmkuhl. "An Operational Analysis for Air Force 2025: An Application of Value-Focused Thinking to Future Air and Space Capabilities." Research paper, Air Force 2025. Maxwell AFB, AL: Air University, May 1996.

Johnson, Les. "The Tether Solution." *IEEE Spectrum* 37, no. 7 (July 2000): 38–43.

Joint Publication (JP) 3-13. *Information Operations*, 13 February 2006.

Jung, Erik, Matthias Koch, Stefan Schmitz, Ronnie Boutte, Ian Harvey, Taylor Meacham, and Florian Solzbacher. "Miniaturized Camera System Using Advanced Packaging Techniques." In *Proceedings of the 2008 IEEE Electronic Components and Technology Conference.* Lake Buena Vista, FL, 27–30 May 2008, 819–23.

Kim, Jinseok, Sungwook Yang, Jeongeun Baek, Sewan Park, Hyeon Cheol Kim, Eui-Sung Yoon, and Kukjin

Chun. “Cardiomyocytes Self-Powered Polymer Microrobot.” In *Proceedings of the International Solid-State Sensors, Actuators, and Microsystems Conference–Transducers 2007*. Lyon, France, 10–14 June 2007, 1405–8.

Kitching, John, Svenja Knappe, Peter D. D. Schwindt, Vishal Shah, Leo Hollberg, Li-Anne Liew, and John Moreland. “Power Dissipation in a Vertically Integrated Chip-Scale Atomic Clock.” In *Proceedings of the 2004 IEEE International Frequency Control Symposium and Exposition*. Montreal, Canada, 2004, 781–84.

Kladitis, Paul E. “Materials for Harsh Environments.” Presentation. Microelectromechanical Systems (MEMS) Professional Development Course for Weapon Systems Applications. Picatinny Arsenal, NJ, 31 October 2000.

Kladitis, Paul E., and Victor M. Bright. “Prototype Microrobots for Micro-Positioning and Micro-Unmanned Vehicles.” *Sensors & Actuators A: Physical* 80, no. 2 (2000): 132–37.

Kubo, Yayoi, Isao Shimoyama, and Hirofumi Miura. “Study of Insect-Based Flying Microrobots.” In *Proceedings of the 1993 IEEE International Conference on Robotics and Automation* 2. Atlanta, GA, 2–6 May 1993, 386–91.

Mait, Joseph N. “The Army Research Laboratory’s Program on Micro-Autonomous Systems and Technology.” *Proceedings of SPIE* 7318 (11 May 2009): 3.

Miziolek, Andrzej W. “Nanoenergetics: An Emerging Technology Area of National Importance.” *DOD AMPTIAC Quarterly Newsletter* 6, no. 1 (Spring 2002): 43–48.

Mohr, Benjamin B., and David L. Fitzpatrick. “Micro Air Vehicle Navigation System.” *IEEE Aerospace and Electronic Systems Magazine* 23, no. 4 (April 2008): 19–24.

National Research Council Committee on Implications of Emerging Micro- and Nanotechnologies. *Implications of Emerging Micro and Nanotechnology*. Washington, DC: National Academies Press, 2002.

Niles, Christopher, and Thehue Tran. “A Study of Autonomous Micro-Robots and Their Application to Complex Environments, Volume I.” Technical Report ARFSD-TR-00001. Picatinny Arsenal, NJ: US Army Armament Research, Development and Engineering Center, Fire Support Armaments Center, May 2000.

Parviz, Babak A., T. K. Allen Chou, Chunbo Zhang, Khalil Najafi, Michael 0. Muller, Peter D. Washabaugh, and Luis P. Berna. "Performance of Ultrasonic Electrostatic Resonators for Use in Micro Propulsion." In *Proceedings of the 14th IEEE International Conference on Micro Electro Mechanical Systems–MEMS 2001*. Interlaken, Switzerland, 21–25 January 2001, 586–89.

Ren, Tian-Ling, Hao Chen, Yi Yang, Yi-Ping Zhu, Di Fu, Chao Wang, Xiao-Ming Wu, Jian Cai, Li-Tian Liu, and Zhi-Jian Li. "Micromachined Piezoelectric Acoustic Device." In *Proceedings of the 2009 2nd International Workshop on Electron Devices and Semiconductor Technology.* Mumbai, India, 1–2 June 2009, 1–6.

Rosenfeld, Wenjamin, Fredrik Hocke, Florian Henkel, Michael Krug, Norbert Ortegel, Julian Hofmann, Markus Weber, and Harald Weinfurter. "Long-Distance Atom-Photon Entanglement." In *Proceedings of the European Conference on Lasers and Electro-Optics 2009 and the European Quantum Electronics Conference: CLEO Europe–EQEC.* Munich, Germany, 2009, 1.

Secretary of the Air Force, *United States Air Force Unmanned Aircraft Systems Flight Plan 2009–2047.* Washington, DC: Headquarters, Secretary of the Air Force, 18 May 2009.

Secretary of Defense. *FY 2009–2034 Unmanned Systems Integrated Road Map.* Washington, DC: Department of Defense, Office of the Secretary of Defense, 6 April 2009.

Shimoyama, I., Y. Kubo, T. Kaneda, and H. Miura. "Simple Microflight Mechanism on Silicon Wafer." *Proceedings of the IEEE MEMS Workshop*, 1994, 148–52.

Solem, Johndale. "The Application of Microrobotics in Warfare." Technical Report LA-UR-96-3067. Los Alamos, NM: Los Alamos National Laboratory, 1996.

Son, C., and B. Ziaie. "An Implantable Wireless Microdosimeter for Radiation Oncology." *Proceedings of the IEEE 21st International Conference on Micro Electro Mechanical Systems*, Tucson, AZ, 13–17 January 2008, 256–59.

Stern, Liron, Avinoam Stern, and Benny Levy. "The Nano-Atomic-Clock." In *Proceedings of the IEEE International Conference on Microwaves, Communications, Antennas, and Electronics Systems–COMCAS 2009.* Tel Aviv, Israel, 2009, 1.

Syms, Richard R. A., Eric M. Yeatman, Victor M. Bright, and George M. Whitesides. "Surface Tension-Powered Self-Assembly of Microstructures—The State of the Art." *Journal of Microelectromechanical Systems* 12, no. 4 (August 2003): 387–417.

Trimmer, W. S. N. "Microrobots and Micromechanical Systems." *Sensors and Actuators* 19, no. 3 (1 September 1989): 267–87.

Volkel, R., M. Eisner, and K. J. Weible. "Miniaturized Imaging Systems." *Journal of Microelectronic Engineering* 67–68 (2003): 461–72.

Wang, Shenggui, Liwei Lin, and Hang Guo. "Analysis and Design of a Micromachined Rb-85 Filter in Passive Rubidium Atomic Clock." In *Proceedings of the 4th IEEE International Conference on Nano/Micro Engineered and Molecular Systems–MEMS 2009.* Shenzhen, China, 5–8 January 2009, 911–14.

Weir, Nathan A., Dannelle P. Sierra, and James F. Jones. "A Review of Research in the Field of Nanorobotics." Technical Report SAND2005-6808, System Technologies Intelligent Systems and Robotics Center. Albuquerque, NM: Sandia National Laboratories, October 2005.

Winkleman, Adam, Logan S. McCarty, Ting Zhu, Douglas B. Weibel, Zhigang Suo, and George M. Whitesides. "Templated Self-Assembly over Patterned Electrodes by an Applied Electric Field: Geometric Constraints and Diversity of Materials." *Journal of Microelectromechanical Systems* 17, no. 4 (August 2008): 900–910.

Yeh, Richard, Ezekiel J. J. Kruglick, and Kristofer S. J. Pister. "Microelectromechanical Components for Articulated Microrobots." In *Proceedings of the 8th International Conference on Solid-State Sensors and Actuators and Eurosensors IX.* Stockholm, Sweden, 25–29 June 1995, 346–49.