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Potential Science and Technology Game Changers for the Ground Warfare of 2050: Selected Projections Made in 2017

by Alexander Kott, Kwong Choi, Brad Forch, Piotr Franaszczuk, Shashi Karna, Stephen Lee, Joseph Mait, Peter Reynolds, Brian Sadler, Ananthram Swami, and Bruce West

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by Alexander Kott
Office of the Director, ARL

Kwong Choi and Joseph Mait
Sensors and Electron Devices Directorate, ARL

Brad Forch and Shashi Karna
Weapons and Materials Research Directorate, ARL

Piotr Franaszczuk
Human Research and Engineering Directorate, ARL

Stephen Lee, Peter Reynolds, and Bruce West
Army Research Office

Brian Sadler
Vehicle Technology Directorate, ARL

Ananthram Swami
Computational and Information Sciences Directorate, ARL

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14. ABSTRACT

This report, written by the members of the Strategic Projections Committee of the US Army Research Laboratory (ARL), is a “think piece”. Its intent is to offer the Army community the thoughts of ARL scientific and technology professional–level scientists on the likely breakthroughs in science and technology that may occur between now and 2050 and have the potential to be game changers for ground warfare in 2050 and beyond. This report will be followed by more reports of such nature, possibly on an annual basis. The subsequent reports might offer different projections or update those already discussed. In effect, it is a living document that is not intended to offer arguments or recommendations for programmatic investments or priorities. It touches on the following topics: artificial cells; algorithms that will enable creation of “seeing skins” for high resolution, 3-D imaging; IR sensors that would be dramatically smaller, cheaper, and more sensitive and multifunctional than what is available today; ways to measure, distribute, and exploit quantum entanglement; self-healing, self-protecting, and other such networks; brain-to-brain and brain-to-artificial-intelligence interfaces; integration of neuroscience and conventional computing; and Complexity Science that will enable new methods to anticipate and mitigate failures.

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1. Introduction

This report is written by the members of the Strategic Projections Committee of the US Army Research Laboratory (ARL). The committee comprises all scientific and technology professional (ST)–level scientists of ARL—a total of 10 as of 2017—and is chaired by the Chief Scientist of ARL.

The report should be seen as a "think piece". Its intent is to offer the Army community the thoughts of ARL STs on the likely breakthroughs in science and technology (S&T) that may occur between now and 2050 and have the potential to be game changers for ground warfare in 2050 and beyond.

We anticipate that this report will be followed by more reports of such nature, possibly on an annual basis. The subsequent reports might offer different projections or update those already discussed. In effect, it is a living document.

It is also important to emphasize what this document is *not*.

It is not intended to offer arguments or recommendations for programmatic investments or priorities. There are appropriate venues and processes for such deliberations, and this is not one of them.

Furthermore, the potential breakthroughs described here are not intended to constitute either an exhaustive list or even a list of most significant items. It is simply a selection—driven by interests, intuition, and expertise of individual STs—from a broad space of possible breakthroughs.

Consider Fig. 1. There are many potential S&T breakthroughs that may occur between now and 2050; these are depicted by the stars inside the left circle. Most of them will not have a game-changing importance for ground warfare in 2050. There are also many potential game changers for ground warfare in 2050; these are depicted by the stars inside the right circle. Most of them are not based on S&T breakthroughs (some will be dependent on existing S&T, some on things not related to S&T). However, at the intersection of the 2 circles in Fig. 1 there are breakthroughs with game-changing implications. That is also a potentially large set. From that set we selected a few items to discuss in this report.

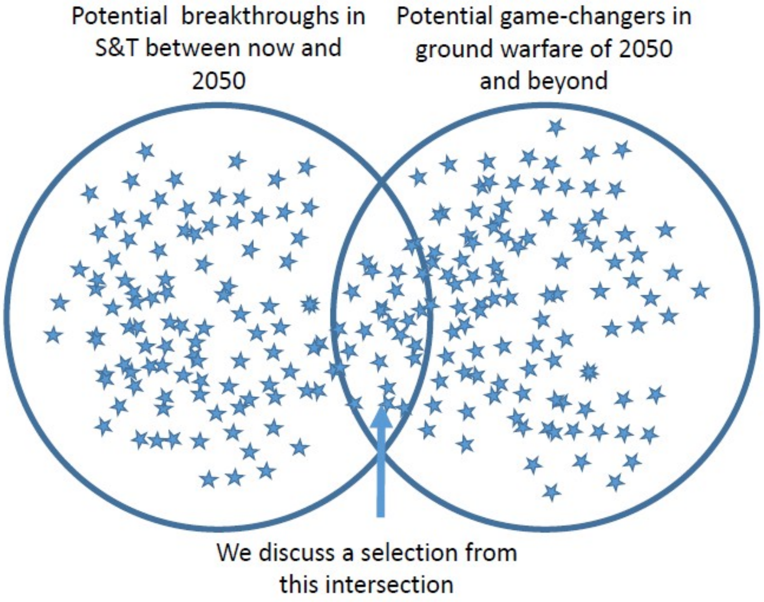

Fig. 1 This report discusses a selection (not prioritized) from the subspace of potential S&T breakthroughs that may also have game-changing implications for ground warfare

We do not assume that the United States has a monopoly on any of these S&T breakthroughs or on the resulting game-changing military capabilities. We do not project which country or countries will elect to pursue any of these research directions, or will be successful in such research and development (R&D) efforts, or will prioritize the development of practical systems based on such breakthroughs. The decisions and outcomes of this nature depend on complex social, economic, political, and military factors that are far beyond the scope of this report.

The following is a summary of the report:

- Projected breakthroughs in creation of artificial cells will enable on-demand, on-base production of high-value molecules, significantly reducing the logistics tail and associated transport and storage costs.
- Projected breakthroughs in algorithms that combine images to produce a coherent aperture in near real time will enable creation of "seeing skins" for high-resolution, 3-D imaging in the visible and IR bands over a large field of view.
- Projected breakthroughs at the intersection of artificial layered semiconductor materials, near-field electromagnetics (EM), and quantum optics will enable IR sensors that would be dramatically smaller, cheaper, and more sensitive and multifunctional than what is available today.

- Projected breakthroughs in ways to measure, distribute, and exploit quantum entanglement will enable ultra-precise timing and time distribution, improved sensing, faster information processing, and new security in communications that are impossible by any other means.
- Expected breakthroughs in understanding and enabling self* (e.g., self-healing, self-protecting, and the like) properties of networks, coupled with advances in adversarial machine learning and adversarial reasoning will enable resilient reliable networking in an adversarial environment.
- Projected breakthrough in brain-to-brain and brain-to-artificial-intelligence (AI) interfaces will enable high-performance warfighting teams that understand each other in complex operations, nearly instantly, without any verbal communications and even with little training.
- Projected breakthroughs in integration of neuroscience and conventional computing into AI will lead to omnipresent, highly distributed machine intelligence embedded within a multitude of physical objects surrounding and teaming with the warfighters.
- Projected breakthroughs in Complexity Science, particularly in Fractional Calculus, will enable new methods to anticipate and mitigate failures in planning exceptionally complex operations like interventions in megacities.

2. Artificial Cells

Authors: Dr Stephen Lee (ST) and Dr Stephanie McElhinny

Bottom line up front (BLUF): Projected breakthroughs in the creation of artificial cells will enable on-demand, on-base production of high-value molecules, significantly reducing the logistics tail and associated transport and storage costs.

Artificial cells, nonliving structures that are compatible with biological cellular machinery, will provide a robust, predictable, nonautonomous platform for the execution of human-designed biological programs to realize novel capabilities for the ground warfare of 2050. These artificial cells will serve as nonbiological reaction vessels that 1) sequester human-designed biological programs and the molecules needed to execute these programs, 2) control the release of the products of these programs to the exterior of the cells, 3) execute programs only when triggered, with no spurious activity and high signal to noise, 4) can be stored in an inactive state for extended periods of time with highly reliable “reboot” when needed, and 5) are able to execute their programs over a wide range of environmental conditions experienced during military operations.

Over the past few years, researchers have demonstrated several complex characteristics and functions akin to living cells in artificial systems. Various approaches have been used to assemble artificial membranes to create artificial cell-like structures comprising natural phospholipids, synthetic phospholipids, or synthetic polymers. Simple human-designed biological programs have been successfully executed within the interior of artificial cell structures. The transport of materials into and out of artificial cells has been demonstrated, as well as exchange of material between different species of artificial cells. Artificial cells have also been designed that can internalize external material to replicate cellular "feeding". Other artificial cells were created with active elements of the cytoskeleton encapsulated within that enabled the cells to change shape and move. Recent work has also demonstrated an approach that enables artificial cells to self-proliferate for multiple generations, akin to the replication and division of living cells.

While these recent accomplishments demonstrate the impressive replication of complex and dynamic functions of living cells, thus far each of these has been demonstrated in one, or at most a few, discrete artificial cell systems. Over the next 25–30 years, just as continued advances in synthetic biology will expand the complexity of engineered living systems, research focused on artificial cells will build toward major breakthroughs that will integrate discrete artificial cell functions into a coordinated artificial cell platform, enabling the vision outlined of a robust, versatile on-site manufacturing capability.

Living cells are able to generate all of the energy required to produce the molecules needed to sustain function. Because artificial cells are by definition nonliving, a certain level of external intervention will be necessary to sustain the activity of these artificial cells. Future research will identify those functions that are amenable to internalization within the cells for autonomous activity and those which must be externally controlled via engineered systems. For artificial cells to serve as robust and predictable chassis for engineered biological programs, they must remain as simple as possible but must also require minimal human intervention to serve as a feasible option for an on-site manufacturing platform.

While the autonomous production and degradation of proteins and small molecules within artificial cells will be optimized to minimize the extent of external intervention, delivery systems will be designed to supply critical molecules required for artificial cell function that are not autonomously produced, and similar approaches may be necessary for the clearance of waste products to prevent failure or collapse of the artificial cell platform. Engineered systems may also be utilized to repeatedly regenerate the artificial cell population once the production capacity of a current population is exhausted. The need to strike a balance between autonomous cell-like activities executed by the artificial cells and external engineered systems that support these autonomous artificial cell functions provides a unique paradigm where capabilities of the artificial cell platform will evolve with the continuous integration of independent advances in biology and engineering.

Research in this area will likely demonstrate and integrate several key characteristics of living cells required for the successful execution of biological programs in an artificial cell, including the following:

1) Generation of a membrane-like structure that segregates internal contents from the external environment and allows for controlled transport into and out of the artificial cell but has increased stability relative to biological lipid bilayers
2) Optimization of protein translation and degradation systems within the artificial cell
3) Development of structures to control spatial organization of internal components, similar to natural organelles within living cells, including artificial structures designed to target specific reaction components to a given structure and to organize these components in 3-D space for maximum reaction efficiency
4) Introduction of transport systems and methods to control transport both into and out of the artificial cell as well as within the cell
5) Development of strategies to achieve spatiotemporal control of execution of engineered biological programs within the artificial cell
6) Design of approaches to endow artificial cells with the ability to “ingest” external material akin to cellular “feeding” via phagocytosis

With these breakthroughs, artificial cells will deliver remarkable new capabilities by 2050 from which important pharmaceuticals, fuel sources, and even food can be produced on demand in the field. The production of high-value biological and nonbiological products in the field will also revolutionize additive manufacturing beyond production of traditional structural materials. Artificial cells will revolutionize logistics for the ground warfare of 2050 by enabling on-demand, on-base production of high-value molecules, significantly reducing the logistics tail and associated transport and storage costs. An artificial cell platform could be programmed with the capacity to produce a large library of different pharmaceutical molecules, with the specific program that is executed in a given scenario triggered upon exposure to a blood sample from an infected warfighter. Biomarkers in the blood would trigger the production of the appropriate medical countermeasure or treatment, significantly reducing the need for cold chain storage in the field and providing a capability akin to a “pharmacy on a chip”. Artificial cells could also be programmed to produce inorganic materials that serve as precursors for additive manufacturing, supporting the vision of self-sustaining field operations that no longer require transport of replacement parts for engineered systems.

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3. Computational Synthetic Aperture Imaging

Author: Dr Joseph N Mait, ST

BLUF: Projected breakthroughs in algorithms that combine images to produce a coherent aperture in near real time will enable creation of “seeing skins” for high-resolution 3-D imaging in the visible and IR bands over a large field of view.

In 2050, advances in imaging science, optical technologies, detection, and signal processing, as well as integration, will have enabled “seeing skins” that one can apply to building interiors, building exteriors, and to the exteriors of all mobile platforms, both air and ground. “Seeing skins” will provide the military with increased capabilities in situational awareness such as high-resolution 3-D imaging in the visible and IR bands over a large field of view.

If current trends in fabrication technology continue, it should be possible in the near future to create monolithic arrays of cameras in a manner similar to the high-pixel-count detectors of today. Such camera arrays will be sufficiently thin that it should be possible to embed them into interior and exterior walls of buildings and on the exterior of vehicles, both ground and air.

Although it is possible to *derive* information about a scene by combining images from individual cameras in an array, so long as the cameras are incoherent to each other there can be no increase in the information capacity of the system. To increase information capacity requires that the camera apertures be coherent with one another.

To understand this, consider 2 photons released with the same energy at the same time from a single point in the scene. These 2 photons are detected by the 2 cameras farthest apart in the array. If their outputs are combined on an intensity basis, the output is an irradiance value given by the average irradiance of the 2 photons. However, if the cameras are coherent, the irradiance output depends upon the distance between the scene point and each camera and the distance between the cameras. If there is zero output for a particular wavelength, we can deduce that the distance from the cameras to the scene point differs by half a wavelength. If the output is twice the irradiance of a single photon, the distances differ by wavelength. If the camera array is coherent, by examining all possible combinations it is possible to localize the scene point.

Phase coherence is the foundation upon which synthetic aperture radar is built and is possible due to the relative ease with which one can measure phase at radio frequencies. To so requires a reference against which phase differences are measured. Using a coherent reference is also the essence of holography and interferometry. It allows phase to be encoded in an intensity measurement.

However, what if using a coherent reference is not possible or undesired? For example, actively probing a scene with a light source could compromise a mission. In such situations, advances in computational imaging have shown that a reference may not be necessary. Instead, through signal processing, it is now possible to estimate the phase of an intensity image using an iterative technique that exploits the relationship between the image and its spatial frequency spectrum. If this technique is applied to individual cameras in a camera array and across the array, one should be able to create a large coherent aperture. This improves optical performance, especially resolution. If one can do this over a single camera array, it is also possible to combine coherent images from spatially separated camera arrays and, in so doing, provide multiple perspectives to create 3-D images with high resolution.

Although it is possible to create a camera with a single large aperture, for such a system to produce a high-resolution image requires a volume given by the cube of the aperture diameter. The synthetic coherent combination of cameras in an array should provide equivalent optical performance but in a greatly reduced volume. However, the tradeoff is increased postdetection processing.

Currently, smartphone manufacturers are driving toward multiple cameras on a single platform. In the next 5 years one can expect arrays with a small number of cameras (e.g., 1 × 4) on smartphones. Over several decades, one can expect array sizes to increase. One can also expect array processing power to increase concomitantly. Within 15–20 years, the technology should be available to realize a moderately sized camera array (e.g., 8 × 8 or 16 × 16) with onboard processing in a package that is 1 cm thick. The missing element is the processing necessary to combine the images to produce a coherent aperture in near real time. Effort is required to generate the algorithms to do this.

The key to phase retrieval is developing constraints that reflect accurately the physics that allow one to extract information embedded in an intensity measurement. Computational phase retrieval was developed nearly 40 years ago to retrieve the phase from a single intensity measurement of an astronomical object. However, researchers have recently used phase retrieval to improve the resolution of microscopes. The technique, referred to as Fourier ptychography (ptycho from the Greek for folding), first retrieves the individual phases from a series of incoherent microscopic images. Retrieving the phase for each image enables them to be combined coherently via computation. The technique improves microscope resolution several-fold beyond the classical resolution limit and underscores the capacity for information extraction inherent in physics-based postdetection computation. The results indicate the potential for applications in more-complex environments.

However, such results are possible because the scenes contain a small number of point objects over a small range of distances. In contrast to microscopy, intelligence, surveillance, and reconnaissance applications have virtually no control over the imaging environment. Outdoor scenes consist of a large number of objects of various sizes, materials, and distances. Current active techniques for measuring distances, for example light detection and ranging (Lidar), are already challenged. We complicate this by replacing active means with passive and use processing to generate phase estimates comparable to the active system.

Present phase retrieval constraints assume the measuring instrument has a finite aperture, that real objects have a finite extent one can estimate, and that processed measurements retain their intensity character (i.e., they remain nonnegative and real). Extending phase retrieval to more-complex scenes requires modifying or adding constraints to account for a large number of points in a single plane and ensuring phase estimates from different cameras are consistent with each other. Given the short wavelength of light, extending the range over which one can estimate object phase is the most difficult challenge. However, applications such as monitoring corridors in buildings provide an opportunity to develop and deploy intermediate systems that use computational coherent combination over limited distances.

If this capability can be demonstrated, it will also enable one to opportunistically combine different camera arrays within a region to form an adaptive imager with no moving parts. The combination of integration and signal processing, in effect, creates both a phased camera array and a phased array of camera arrays.

These techniques are amenable to imaging in the visible and in the IR portions of the spectrum. Thus, dual-waveband systems would provide operational commanders co-registered 3-D high-resolution spatial maps of the visual scene and the heat map.

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4. Miniaturized Multifunctional Quantum IR Sensors

Author: Dr Kwong-Kit Choi, ST

BLUF: Projected breakthroughs at the intersection of artificial layered semiconductor materials (ALSMs), near-field electromagnetics (NFEM), and quantum optics (QO) will enable IR sensors that would be dramatically smaller, cheaper, and more sensitive and multifunctional than those available today.

IR detection serves many important military functions, as it detects light sent out by the target itself. It is often applied to large-area surveillance, autonomous navigation, gunsights, missile intercept, chemical and biological detection, situational awareness at night in a visually degraded environment, and the like. Ideally, an IR sensor is sensitive and fast, displays pictures in high resolution and in color, is inexpensive and readily available, and is lightweight and draws little power—in short, like current cell phone cameras. In addition, it should be multifunctional, providing such capabilities as multispectral and hyperspectral imaging for target recognition and identification, polarization-sensitive imaging for detecting manmade objects, Lidar imaging for ranging, and the like. The S&T that enable the realization of miniaturized multifunctional quantum IR sensors will be crucial for ground warfare of 2050 in maintaining superior situational awareness on the battlefield.

The prerequisite S&T are ALSMs, NFEM, and QO. The advances in ALSMs will produce IR materials that are of high quality, readily available, and low cost. They are needed for ubiquitous application of these sensors. The advances in NFEM, on the other hand, will reduce dramatically the size, weight, power, and cost (SWaP-C) of IR imaging systems with the benefits of advanced functionality, allowing for their seamless integration and expansion into relevant warfighting platforms. Ultimately, NFEM will bring single-photon sensitivity onto the battlefield to detect ultra-low-observable targets. Single-photon sensitivity provides Soldiers not only superior vision, but also new capabilities. The advances in QO will enable the ground warfighters to exploit new phenomenology brought by the quantum nature of light. A quantum sensor with single-photon sensitivity is going to provide higher temporal and spatial resolutions through entangled photons and higher-order coherences. The QO methodology will be utilized to design these sensors and their systems. Manipulating and detecting quantum states of light in the IR regime will offer an ultimate advantage in situational awareness.

Different from the low-cost, readily available silicon material used in visible cameras, IR detection in the long wavelength is based on a more-exotic, scarce bulk material. This material is costly and difficult to produce in large quantities. Recently, the Office of the Secretary of Defense funded a detector material program, Vital Infrared Sensor Technology Acceleration. This program explored a new type of semiconductor material known as strained layer type-II superlattices.[1] This material gains its desirable optical properties by forming alternate atomic layers of 2 different semiconducting materials with which the material energy band structures can be fundamentally changed. The resulting material shows promising properties and can be produced in larger quantities. Further investigations into similar and other artificial layered materials may provide even better choices.

The size of a sensor chip determines the SWaP-C of an imaging unit. To maintain the same resolution of a chip while its size is reduced, individual pixels have to shrink accordingly. Traditionally, IR sensors employ pixel size larger than 20 μm. It is much larger than the 1–2 μm used in cell phone cameras. This large difference is mainly due to the much longer absorption length in IR materials. It will usually take a 10-μm-thick material to absorb a significant amount of light. Manufacturing process dictates that separation of the pixels be significantly larger than their thickness, and thus the pixel pitch is much larger than 10 μm. To solve this difficulty, one needs to invent optical structures that can enhance light–matter interaction in a small volume. Recently, ARL invented a resonant structure that can capture and trap incident light until it is absorbed.[2] With this structure, one can reduce the layer thickness by a factor of 10 to about 1 μm. As a result, effective detectors have been demonstrated down to 6-μm pixel pitch, and the 3-μm node is currently being pursued.[3]

Although a pixel of 6 μm can already reduce the unit SWaP-C by a factor of 10 or more, it is still behind the visible camera. Further investigation into NFEM will be able close this gap. In addition, new electromagnetic (EM) structures will be able to create special functionality such as efficient hyperspectral imaging, polarization-sensitive imaging, and high-speed heterodyne imaging.

The incident light excites surface plasmon polariton (SPP) waves[4] inside ARL's resonant detectors, and therefore they exhibit much shorter wavelengths than the optical wavelengths in the material. For example, the mode volume of the SPPs is only about $1 \times 1 \times 1\ \mu m^3$ for the 10-μm incident light in free space. If the mode volume can be further compressed to $0.1 \times 0.1 \times 0.1\ \mu m^3$ using certain EM nanostructures such as photonic crystals,[5] nano-antennas,[6] metamaterials,[7] or the like, the intensity of single photons will be strong enough to place light–matter interaction in the strong coupling regime. In this regime, cavity quantum electrodynamics[8] dominates and the corresponding sensor can acquire single-photon sensitivity, a sensitivity that is several orders of magnitude higher than a classical sensor. Not only will this sensitivity provide Soldiers with far superior vision, but a quantum sensor can also exploit the quantum nature of light to realize new capabilities, such as higher temporal and spatial resolutions using entangled photon pairs, squeezed light, higher-order coherences, photonic de Broglie wave, or the like.[9] The study of QO will help the design of these sensors and their utilization. The Defense Advanced Research Projects Agency (DARPA) launched a Quantum Sensors Program in the past to look into the possible advantages of quantum sensing. However, this and other studies have been concentrated in the visible and near-IR wavelengths. Future advances in QO in the long-wavelength IR are going to greatly enhance the sensing capability of ground warfighters.

Although near-field EM and QO have been pursued extensively in open literature in the radio and visible spectra, respectively, the extension to the long-wavelength IR wavelengths has been scarce. Treating IR light as coherent EM waves on one hand and quantum particles on the other can utilize many of the RF and QO concepts and methodologies in realizing IR detectors with unprecedented sensitivity and functionality.

Strained layer type-II superlattices[1] and quantum-well IR photodetectors[2] are 2 recent examples of ALSM that show certain advantages over conventional bulk materials. The search for other layered materials and 2-D materials such as graphene[10] is continuing. The design of complex EM structures shows good progress due to the improved numerical solutions to Maxwell's equations using today's more powerful computer hardware and software. ARL's resonator-pixel technology is one prime example. One can expect ingenious designs to be available in near- and mid-term that can increase light–matter interaction in ever decreasing optical volume. Significant SWaP-C reduction along with increasing sensitivity and functionality will change how these sensing units being embedded, integrated, and utilized in military systems. In the far term, when the sensing volume is sufficiently small such that cavity quantum electrodynamics operates, another significant capability enhancement via QO will be realized.

There are alternatives in detector materials such as using alloyed materials rather than layered materials. The layered materials, however, possess more structural parameters one can control to optimize their opto-electronic properties. The trend of smaller sensors is inevitable.

In summary, by 2050, miniaturized multifunctional quantum IR sensors will be possible as a result of breakthroughs in 3 technical areas: ALSMs, NFEM, and QO. To achieve single-photon detection, which is the ultimate limit for sensor sensitivity, each incoming photon will be confined in an extremely small space so that its intensity is large enough to couple strongly to an absorbing medium. The medium itself will be in nanoscale.

Suitable materials do not exist yet, but they will be made of ALSMs that are only one or a few atoms thick, such as graphene and quantum wells. However, these 2 examples have their own challenges and may not be the ultimate solution. Nevertheless, based on the current trend of ALSM research, suitable material will be available in the next decade. After a suitable material is identified, one can then proceed to devise a physical mechanism to compress the natural optical mode volume by orders of magnitude so that the electric field of each photon can drive the prerequisite quantum Rabi oscillations[8] for single-photon detection. The currently known EM approaches, such as using tightly bounded surface plasmons, are not able to compress the optical mode to such a great extent. However, further research into different NFEM phenomena will be able to close this gap. After roadblocks in these 2 areas are resolved, single-IR-photon detection can be realized, resulting in the most-sensitive IR detectors. However, extreme sensitivity might not be unanticipated and could be accounted for by an adversary. QO will bring a sensing capability that is unexpected by generating, detecting, and harnessing quantum states of light. Currently, there are no reliable, strong sources for different quantum states of light in the long-wavelength IR, and quantum IR sensors do not exist. In the coming decades, the research in QO will bring about such a light source and the corresponding sensor. A present candidate for the source/sensor pair is the quantum cascade laser[11]/quantum-well IR photodetector pair, but future advances will certainly produce better options.

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5. Quantum Information Science

Author: Dr Peter Reynolds, ST

BLUF: Projected breakthroughs in ways to measure, distribute, and exploit quantum entanglement will enable ultra-precise timing and time distribution, improved sensing, faster information processing, and new security in communications that are impossible by any other means.

Quantum Information Science is an emerging area of science at the intersection of quantum physics, computer science, information science, and engineering that seeks to exploit the advantages that quantum physics provides over classical physics in all areas. It uses explicitly quantum properties of matter (such as the wave nature of matter, the superposition principle, quantum statistics, and the property Einstein dubbed as “spooky”—namely, entanglement) to break (classical) theoretical limits. That means things like breaking limits on measurement precision, or computational power (computational complexity), or information density, or even what we mean by measurement (e.g., interaction-free measurement). Exploiting all these properties of quantum mechanics to make limit-breaking technologies in computing, sensing, communications, networking, imaging, and other areas are all expected outcomes. In all cases we have ideas of what can be done but by no means the full picture of the possibilities. Even in those areas where we know what can be done, in most cases we do not know how or the best way to implement them. Only very limited parts of this arena are mature today.

Scientific Breakthroughs

At the heart of this second quantum revolution is entanglement, a property of quantum mechanics that was largely ignored over its first half century; and when it was not ignored it was disavowed by people as eminent as Einstein. Only quite recently has entanglement been shown to be a real and an indispensable part of quantum mechanics and, moreover, a property with many significant consequences. We know much about this property but much less about how to exploit it. For example, we know that it enables even greater improvements for sensors (greater sensitivity and precision), but we only have clues how to exploit it to do so. In particular, networking sensors coherently seems like a major opportunity to improve sensing and to exploit nascent quantum networks, but we do not know how to do this yet.

Likewise, we know that entanglement allows for various security protocols for quantum communications. However, how to implement these protocols is not fully understood, and we do not even know the range of possible such protocols. In information processing, we know that quantum coherence and entanglement enable exponential speedups, but we have very few algorithms (though a few extremely important ones) that demonstrate such a speedup. We are just breaking open this aspect of the field with foundational work that points at what can and cannot achieve a “quantum advantage”. Seemingly different topics—different aspects of Quantum Information Science (QIS)—all hinge on breakthroughs we see coming in the understanding and exploitation of entanglement.

Already we have sensors, improved through atom optics (quantum mechanical wave behavior of atoms), that have been demonstrated at Technology Readiness Level (TRL) ~6. Even better sensors and the ability to distribute sensor (and time) information coherently is coming through exploitation of entanglement. Currently, this is only at TRL ~1. Quantum computing is still in its infancy, with only few qubits and relatively few operations possible within the coherence time. (This is strongly dependent on the platform, however, and thus even questions about which platform to use are still at the 6.1 level.) Quantum networks are ripe for study, as they impact communications needs as well as the ability to coherently enhance sensing and time distribution as well as distributed computation. As components of QIS mature, they impact all the other components of QIS.

Potential Impact on Ground Warfare by 2050

The impact of QIS is clearly on all corners of Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance. Traditional limits on sensing, imaging, computing, communication, networking, simulation, and more have all been shown to be enhanceable via exploitation of quantum mechanics. For example, in computation one can expect to get exponential speed-up for certain important algorithms (such as those related to factoring, logistics, optimization, and to solving chemical and materials science problems) and can be exploited in breaking traditional forms of encryption. In imaging, not only can resolution be enhanced beyond classical limits, but new concepts and forms of imaging become possible. Some of these have no classical counterparts, such as interaction-free measurement. In communications, new secret-sharing, authentication/verification, encryption protocols, and secure computing approaches are possible. In sensing, one can not only break classical limits on sensitivity, but also devise a "sensor" that enables secure positioning, navigation, and timing (PNT) in the absence of GPS in a single design, incorporating clock, gyro, accelerometer, and gravimeter (i.e., all components of an international measurement (IMU) into a single design based on trapped ultra-cold atoms.

Why is QIS Crucial to Ground Warfare Capabilities?

PNT in GPS-denied environment is necessary because warfighters will be facing that situation well before 2050. Lack of an alternative to GPS will indeed be game changing (in an unsatisfactory way). QIS is not the only way to achieve PNT in GPS-denied environments. But because all components of an IMU (accelerometer, gyro, gravitomers, and clock) can be enhanced through QIS, it is a particularly easy way to envision achieving this while not giving up on (and in fact improving on) the precision of GPS. Moreover, even at the present level of maturity in QIS, sufficiently good IMUs can be made this way to provide assured PNT without GPS. It is just a matter of engineering them. Continuing basic research in QIS is leading to other ways to achieve each of the necessary components that will have still greater sensitivity, could have improved fieldability and/or SWAP-C, or could increase functionality (such as coherently distributing time). In all cases (even with the mostly mature atom optics approaches) there is no susceptibility to jamming, spoofing, and denial; no need for satellites or pseudolites; and no emissions that could be used to target the user.

QIS can also achieve ultra-precise magnetometry. This can be used for detection of tanks, submarines, and the like at one extreme, or at another extreme in battlefield medicine and in magnetoencephalography and other imaging. The required metrics are very different, and no longer is just the sensitivity relevant but many other things including the measurement volume (which must be very small for medical applications while not small at all for finding a tank). QIS-based magnetometers vary greatly in implementation (atomic vapors, nitrogen vacancy diamond color centers, Bose Einstein condensates, and more), with remarkably different physics and very different potential realms of application, yet all are QIS-enhanced magnetometry.

Security in communications is a key need now as well as in 2050. QIS can provide provably unbreakable codes and protocols such as the ability to appropriately share secret information with only authenticated individuals. These things are not possible in any other way, since classical information can be readily copied, but by the "no cloning" theorem, quantum information cannot be.

Even now we need better ways to optimize all classes of problems from logistics to new materials design. These problems will only become more complex, more difficult, and more pressing with fights in megacities and other complex domains. Quantum approaches to these kinds of problems are very promising, from quantum annealing methods for optimization to quantum simulation for materials design. Conventional information processing is up against the wall of NP complexity, which these approaches get around.

What Has Been Done?

There has been 20+ years of research (and still going strong) on all fronts of QIS. Small components of QIS, particularly on clocks and atom-optic-based sensing, have reached a level of maturity such that items are already being marketed by small companies. Many other aspects are still completely nascent. Pieces of QIS are at TRL levels ranging from 0 to 6–7. Already from all this we have gained much, including fielded items such as the US Department of Defense's (DOD's) Master Clock that drives the time used in GPS. We have learned algorithms for future quantum computers that break encryption and protocols for quantum communications that ensure secrecy. Many more algorithms and protocols need to be discovered, and even the ones we have are useless without quantum computers and quantum networks to put them on. Steps along each of these paths have been made (e.g., we are approaching 50 qubits, which may seem like very little but is in fact major, as each step up was at one point questionable). Despite this, we are still a long way from practicality (think how many bytes we use in classical computing).

Pieces of the topic (laser cooling, for example) started in the 1970s. Quantum computing per se began in the 1980s. There was essentially no interest until Shor's algorithm showed the power of it in 1994. An Army Research Office (ARO)/Army Aviation and Missile Research, Development and Engineering Center workshop the following year caused the creation of the ARO Quantum Computing (now QIS) program. This program was the basis for first DOD, then US, and subsequently world-wide interest in the topic. The numbers of publications in QIS (and the sub-areas of QIS) continue to climb quickly. Each sub-area has had many significant breakthroughs each year for more than a decade. Looking at the numbers of breakthroughs, or alternatively the numbers of publications or almost any other metric, QIS is growing ever more rapidly than it has in the past. It is growing exponentially and continuing to speed up as other countries begin to participate ever more extensively. China has begun to invest extremely rapidly over the past 5 years or so. Europe and the United Kingdom (UK) have invested far longer, but have massively ramped up in the past 2–4 years, with the UK quantum hubs being one example with each of 4 hubs focusing on a distinct quantum technology.

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6. The Future Resilient Tactical Network

Author: Dr Ananthram Swami, ST

BLUF: Expected breakthroughs in understanding and enabling self* properties of networks, coupled with advances in adversarial machine learning and adversarial reasoning will enable resilient reliable networking in an adversarial environment.

Future military operations will involve teams of highly dispersed warfighters and agents (robotic and software) operating in distributed, dynamic, complex, and cluttered environments. The Army tactical network of 2050 will likely be a coalition network. In a megacity environment, the network will be inundated with joint/coalition threat force and civilian (blue, red, and gray) sensors, radios, precision shooters, robots, and networks of networks. Radio communications are, hence, likely to be congested and contested; networks often will be disconnected, intermittent, and have low bandwidth (disconnected low bandwidth). The coalition force itself will be dynamic, and the network will face the usual resource constraints: bandwidth, spectrum, power, and latency. In addition, extreme dynamics and peer adversary threats will shorten response times, leading to emphasis on quality of information metrics: precision, accuracy, stringent delivery deadlines, and freshness of information, as well as severe constraints on low-probability of detection and low probability of intercept. Peer adversary threats will include cyberattacks, electronic warfare (EW)/jamming, node compromise/loss, and the like. The future network will be largely ad hoc ("MANET") but will make use of infrastructure, both blue and grey, when feasible. Advanced cyber software will enable access to local (gray) communication assets. Communication capabilities will be multi-radio and hybrid, encompassing traditional and nontraditional RF as well as other modalities.

The tactical network supporting the future force will face unique challenges due to its expeditionary nature and the expected engagement with peer adversaries. Interconnectedness, interdependence, heterogeneity, expected high data rates, network size, and configuration parameter space size, coupled with decentralization, result in complexity of network operations and understanding and create numerous opportunities for disruption (environmental, adversarial, or accidental). The complexity, high dynamics, and persistent transients expected in such a network will make reasoning difficult, particularly when response times must be short. The tactical network of 2050 will be intuitive to use, self-organizing, and self-healing, relieving the Soldier of the complexity of network management. It will provide every Soldier with resilient and redundant connectivity on the move and everywhere. It will ensure distributed data analytics so that the right information is readily available.

Today's tactical network is beset with multiple challenges. The tactical network is vulnerable to EW and cyber threats. High-power RF emissions leave Soldiers vulnerable to geolocation and hence jamming and other cyber/EW threats. The available spectrum is increasingly limited and discontinuous, and usage is inefficient largely due to reliance on single modality waveforms. The tactical network is really a network of disparate networks; the daunting complexity makes it hard to secure and hard to operate.

But there are several precursors that lend credence to the 2050 operating picture described earlier.

Expected breakthroughs in understanding and enabling autonomous self-healing, self-protecting, and self-organizing capabilities will ensure continuity, security, and resiliency of the future tactical coalition network. A new DARPA Radio Frequency Machine Learning Systems program seeks to apply machine learning (ML) to design reconfigurable front ends and enable spectrum awareness. But, going beyond, advances in ML are required to enable resource discovery, characterization, and allocation. These breakthroughs will provide insights that will enable advanced ML to autonomously infer and summarize network state at multiple scales; generate security policies; enable efficient solutions to hard optimization/allocation problems (e.g., security monitoring, network, communication modality, channels, antenna selection/configuration, power, and waveform); PHY-MAC-NET layer parameter (re)configuration for rapid and secure anticipatory networking; and learning for topology control and reasoning about information dissemination. Given the adversarial nature of the environment and the distributed nature of the tactical network, ML solutions will be distributed, robust to adversarial interference and deception, adaptive and on-line. Active learning may be useful to limit overhead. There is a tremendous amount of work in academe and industry on general ML problems and on applications to communications problems, with growing interest in adversarial ML (e.g., ARL Cyber Security Collaborative Research Alliance [CRA]). Breakthroughs are expected in obtaining fundamental limits of learning in such an adversarial environment.

At the physical layer of the radio, there have been recent developments in exploring the RF spectrum beyond the conventional 1–10 GHz. These include terrahertz and millimeter wave communication (MMWC) and free-space optical and UV communication. Smart phones already have multiple radios (permitting seamless switching between WiFi, Bluetooth, and cellular, for example), and multimode single devices integrating RF and non-RF waveforms are emerging, which will lead to situation-adaptive multiwaveform networks by 2050. Emerging 6G and proposed 7G standards will integrate 5G networks with satellite networks, and the Army will increasingly use cubesats and smallsats, which along with other communication modalities will ensure “always-connected, everywhere-connected”. Directional networking will be enabled by ongoing work in massive multiple input and multiple output (MIMO) and MMWC. Massive MIMO also enables distributed beamforming and EW and ensures privacy and security. Quantum communications will lead to novel protocols for encryption as well as authentication and verification. Quantum computing will enable distributed computation, leading to distributed allocation of network resources. Advances in quantum information sciences are likely beyond current quantum key distribution (e.g., quantum secure direct communications).

Ensuring seamless switching between different communications modalities presents multiple challenges, some of which are being addressed by the DARPA Collaborative Intelligent Network program/Spectrum Collaboration Challenge with the goal of designing a system in which radio networks will autonomously collaborate to find and use scarce spectrum resources. Emerging advances in molecular communications will enable control of microbots to heal wounds in theater. Growing consumer interest and use of mobile multiplayer gaming, virtual reality, and the Internet of Things (IoT) will drive advances at the networking layer. Group-to-group communication primitives will need to be developed, going beyond unicast and multicast. An emerging emphasis is on information flows rather than packets, and this is crucial to the information sharing nature and needs of the future network. The structure of the network must co-evolve with the information it transports.

Commercial IoT is expanding rapidly in terms of size and heterogeneity of devices. Army IoTs will also include swarms of drones and robotic vehicles; these will pose additional demands on network resources but would also help maintain network connectivity. This will be enabled by expected breakthroughs in distributed control in large heterogeneous and intermittently connected systems. Discovery and use of gray IoT and network assets will be crucial to get situational understanding. The newly established ARL Internet of Battlefield Things CRA will establish the theoretical foundations for understanding complex, tactical, cyber information systems of systems. Expected outcomes by 2030 (at TRL 2/3 levels) include techniques for scalable composition and management of Army IoTs and self-aware ML to enable adaption to dynamic missions and adversarial deception. Army IoTs will face big data challenges of volume, velocity, and veracity. Distributed analytics will be essential to process and fuse this data in real time and to detect and handle corrupted data/ misinformation. Blockchain and similar technologies will mature, resulting in low-complexity algorithms to ascertain provenance of data and prevent tampering. Expected breakthroughs in hardware–software integration will lead to realizable fully homomorphic encryption and secure multiparty computation, thus enabling distributed analytics on a mixture of trusted and untrusted devices.

Software-defined networking is being deployed in the commercial arena due to desirable properties of centralization of command and control as well as separation of data and control planes. A coalition network will likely be frequently disconnected (and often such disconnections may be critical to mission, perhaps to reduce EM signatures), and will likely have multiple distributed controllers. A paradigm shift that enables dynamic allocation of resources—not just communications, but also storage and computing—subject to policy and security constraints will be required. The US-UK Distributed Analytics and Information Sciences International Technology Alliance is exploring the notion of software-defined slices (composed of communications, storage, and computing resources), analytics as a distributed service, and generative policy to cope with these challenges. Expected outcomes by 2030 (at TRL 2/3 levels) include software-defined coalition networking algorithms, and distributed analytics in a heterogeneous setting. Such a generalized SDN approach also enables adaptive deception.

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7. Intelligent Teams

Author: Dr Piotr Franaszczuk, ST

BLUF: Projected breakthrough in brain-to-brain and brain-to-AI interfaces will enable high-performance warfighting teams that understand each other in complex operations, nearly instantly, without any verbal communications and even with little training.

The recent (approximately in the last 10 years) successful implementations of ML algorithms in applications to image recognition have driven rapid development of autonomous systems. Similarly, the development of speech recognition systems radically changed the modes of communications between humans and machines. All of these developments were made possible by advances in artificial neural network algorithms, Convolutional Neural Networks, and, more recently, Recurrent Neural Networks. These network architectures are based mostly on neuroscience research from the mid-20th century.[1] However, in the decades since then neuroscience made significant advances that only now are being incorporated into latest AI algorithms.[2]

Also in the last decade there was a significant progress in brain–machine interfacing driven by needs in rehabilitation medicine. From cochlear implants to robotic limbs controlled by brain and to gene editing, all these developments are poised to transform humanity.[3] Early experiments show the possibility of direct animal brain-to-brain communication exchanging information in real time.[4] These and future enhancements in cognitive performance of humans will greatly enhance capabilities of bi-directional communication with AI-equipped devices and machines, creating emerging capabilities surpassing individual capabilities of machines and humans. Already there are some examples of benefits of teaming intelligent systems (algorithms) with humans to take advantage of different capabilities of artificial and biological systems. One such well-known example is centaur-chess.[5] A recent development in brain–computer interfaces shows advantages from direct coupling of the human cortex with a computer through a bi-directional neural interface.[6]

In the near future these precursors will likely lead to significant breakthroughs in human–human and human–AI interactions. In particular we can expect breakthroughs in development of fast nonverbal direct communication of intent between humans and machines. Verbal communication using natural or even structured language is a significant bottleneck in efficiently performing operational tasks in extreme environments. Mistakes are caused by misunderstanding of the true intent. For example the intention of speaker saying "Go outside!" may be to direct another person or robot to go outside from the room they are in (i.e., "outside of the room"), but the interlocutor may understand it as going "outside of the building". In many situations there is no time to use longer sentences to clarify the intent, and in more-complex situations it is even impossible to precisely communicate the intent. However, if both speaker and recipient of this communication had the same mind reference created by extensive training, the misunderstanding may be avoided.

If the intent (i.e., what the person "had in mind") could be recognized from brain patterns and transmitted directly to the recipient (human or machine), this could be achieved without extensive training. It could also lead to more-efficient delivery of information from artificial agents directly to the brain of human recipients without delay and possible errors in the process of perception through visual or auditory pathways. It can be extended not only to communication between 2 individuals but also teams.

Currently, most efficient human teams achieve a level of communication where team members understand each other without misunderstandings only after extensive training and operational experience, which creates a common mental model. The ability to directly communicate intentions through brain–brain and brain–machine will allow for such team understanding "without words", with much shorter training of both human as well as artificial members. We can expect that it can be realized in the future due to expected technological advances (both hardware and software) in reliable recognizing patterns in the human brain as well as making AI algorithms more flexible and compatible with human perception and processing paradigms. Most advanced AI systems currently operate mostly in a reactive way, learning the mapping from perceptual inputs to actions that maximize future value. In contrast, humans (and animals) can more flexibly select actions based on forecasts of long-term future outcomes using predictions generated from an internal model of the environment learned through experience.[2] Insights from neuroscience may provide guidance to AI that will make seamless team communication and performance possible without extensive training.

These advances in AI and brain–brain and brain–machine technologies will lead to the possibility of creating intelligent teams taking advantage of unique capabilities of enhanced humans as well as advanced AI-equipped machines and devices.

Such teams would be composed of human Soldiers and artificial autonomous agents both physical and virtual (in cyber space). Soldiers will be equipped with wearable and possibly implanted devices augmenting physical as well as cognitive functions. Every agent or device will be equipped with different levels of AI capable of semi- or fully autonomous operation. Thanks to direct communication of intent as well as relying directly information through brain–brain and brain–machine interactions, human and artificial team components will act like networked systems with connectivity level defined by task, situation, and state of each component. Such an intelligent team would be capable of seamlessly incorporating new members (human or agents) without extensive training, reconfiguring the team depending on changing situations, and interacting with a larger network of teams. Some of the information processing, both sensory from immediate environment of the team and information from external sources, can be preprocessed by AI agents, either standalone AI or part of devices augmenting humans, and delivered directly to a human brain, allowing for faster decision making.

By direct-detecting human intent and communicating it nonverbally to artificial agents, the control of machines will be also faster and less prone to errors. However, each member of the team, as well as each team within the network, will be capable of switching into a fully autonomous mode if communications are disrupted or compromised. Due to advancements in AI using an internal model of environment learned in a way similar to human team members, even in autonomous mode, all of the team members' actions will be more predictable and with a higher level of coherence even with no communication.

These teams will have the ability to continuously adapt to changing battlefield situation in complex environments, including megacity and rural environments with mixed adversarial, neutral, or friendly populations, due to ability to consolidate and quickly coordinate individual experiences and capabilities through a common team mental model.

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8. Embedded Artificial Intelligence

Author: Dr Brian M Sadler, ST

BLUF: Projected breakthroughs in integration of neuroscience and conventional computing into AI will lead to omnipresent, highly distributed machine intelligence embedded within a multitude of physical objects surrounding and teaming with the warfighters.

By the year 2050, AI and conventional computing will be integrated into all computing and processing devices. The breakthroughs may lead to omnipresent, highly distributed machine intelligence embedded within a multitude of physical objects that will enable warfighters to readily interact with physical and virtual agents, and these agents will be capable of autonomous action beyond the speed of human response. This will enable Soldiers to team with autonomous agents and dominate tactical environments, although Soldiers will be faced with adversaries with peer AI capability.

Broadly including ML techniques, deep learning (DL) architectures, and knowledge bases, AI has exploded into a variety of commercial applications since 2010. Basic DL paradigms and artificial neural networks (ANNs) date to the 1980s, and 2 trends have enabled their recent emergence. First, digital processing technology has continued its rapid advancement as predicted by Moore's law, such that these algorithms can now be computed in reasonable time on laptop-quality processors. Second, it is now technically feasible to collect and use training data sets at the very large scale needed to ensure good statistical performance with brute-force learning algorithms. Through trial and error, it has become apparent that the best AI performance could require millions of training examples. While it is time-consuming to collect such large validated data sets, digital hardware advances have made it possible to use them to train ANNs.

Embraced by large US commercial enterprises such as Google and Facebook, ANNs have been successfully applied in such areas as image processing and vision, natural language processing, robotics and multi-agent systems. They have displaced decades-old technologies in image and speech processing—problem domains with naturally occurring signals that defied traditional processing methods and were better matched to man-made signals such as communications and radar. ANNs are now better than humans on some kinds of visual object and word recognition as well as gaming. The use of ANNs has enabled driverless cars, whose development is now limited only by cost, legal regulation, and reliance on fixed infrastructure such as maps, roadside electronic aids, signs, road markings, and networking. While there are caveats with regard to robustness and resilience, it can be reasonably expected that intelligent control architectures will emerge with a very high degree of reliability and safety, significantly outperforming human drivers with respect to safety. Of course, this will not entirely eliminate fatal accidents, but their frequency will rapidly diminish as vehicle technology and infrastructure evolve.

For decades there has been a well-known boom-and-bust cycle for AI technology funding and development, sometimes referred to as periods of AI summer and winter. This is not surprising given the general public response to AI. We are simultaneously attracted and repelled by AI; we want smart machines and yet fear what this implies. Historically, human imagination of AI dramatically outperforms our ability to implement it, and the hills and valleys of AI progress are perceived to have very sharp gradients. And AI has a time-evolving definition, because understanding and implementation breeds acceptance and normalcy.

However, the boom-and-bust cycle will flatten out, because recent technology advances have been more practically significant compared with those of the past, which has led to a huge investment in applications and circuits. A new wave of computing devices is now emerging, evolving from graphical processing units that were designed for massively repetitive calculations, primarily consisting of matrix-vector operations that must be repeated in parallel for game graphics updating. The success of DL warrants the large commercial investment in chip development

(100s of millions of dollars). This investment will, in turn, enable further experimental exploration of learning architectures proposed in the past 25 years and create a cycle of theory–experiment R&D. Hence, we can expect further progress without a major pause in momentum.

The result will be 1) a new suite of canonical processing algorithms that will become ubiquitous with general purpose computing, 2) special-purpose devices that will be embedded in virtually all consumer products that have computing electronics (e.g., cameras, phones, and appliances), and 3) embedding into virtually all control systems including mobile platforms (ground and air vehicles) and control networks (e.g., power grid and Internet). The result is AI-everywhere, a massive-scale adoption of AI methods into the commercial infrastructure and products of all kinds.

AI will rapidly become embedded everywhere there are electronics (i.e., everywhere). We are now seeing the first wave of devices, and this will accelerate because the trend is driven by consumer applications and mass distribution. Along with Moore's Law has come a dramatic rise in the cost and complexity of designing and fabricating new integrated circuits, which paradoxically has resulted in a slow decline in the number of new commercially produced circuits every year. The large investment required to produce new devices requires a sufficiently large potential marketplace, so the circuit advances in AI are driven by mass market devices and applications that are to a very large extent commercial and not military.

AI and traditional computing will be integrated, just as digital signal processing has been integrated into circuits over the past few decades. AI will expand to include dynamical inputs such as video streams integrated into control architectures such as robotics and enabled to collaborate via integrated autonomous networking. This future wave of technology convergence will have dramatic implications beyond autonomy, robotics, decision aids, and other areas of current research. For example, current AI architectures may include one or a few DL elements, whereas when AI devices become omnipresent and embedded, hundreds to thousands of these may be combined into complex and dynamic architectures.

With AI globally embedded in all platforms and devices, new intelligent infrastructure will eventually be more locally independent, robust, and resilient to attack. Contrary to today's centralized networks, such as the power grid, which are highly vulnerable and may be subject to widespread failures, intelligent infrastructure will have decentralized intelligence and local adaptivity. Even sources of energy will be dispersed, and adaptive micro-grids will be robust and resilient to large-scale disruption. This same phenomenon will occur with communication networks, which will incorporate wired, directed wireless, omnidirectional wireless, and massive satellite systems, resulting in a highly redundant and resilient system. This is good news for national infrastructure development and protection.

The rich combination of global and local embedding of AI into sensors, robotics, networks, and processing will enable autonomous physical agents that team with Soldiers. These will establish self-healing wireless networks that dynamically defend and utilize infrastructure as available and operate in the cyber and physical domains simultaneously. Intelligent agents will be able to sense and secure areas before Soldiers physically enter the environment, including the ability to detect and map the presence of life, energy sources, and biological agents. Soldiers will also engage with agents to provide directed kinetics in rapid coordinated attacks as well as defend against such attacks.

Distributed collaborative intelligent systems will create a fundamental shift in future warfare, and will become a necessity for the future warfighter to maintain a tactical advantage.

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9. Anticipating Failure in a Complex World

Author: Dr BJ West, ST

BLUF: Projected breakthroughs in Complexity Science (CS), particularly in Fractional Calculus (FC), will enable new methods to anticipate and mitigate failures in planning exceptionally complex operations like interventions in megacities.

Just as error follows a law, failures follow a logic and ultimately so too do catastrophes. The implication of the existence of such a logic is that failing is not solely the result of happenstance but is often the foreseeable, even if unforeseen, consequence of decisions made and actions taken. A recurrent contributor to failure is the mistaken belief that the desired outcome of a complex process can be achieved by actions that follow a linear chain from one cause to the next—like falling dominoes. The linearity assumption that is typically made, even if unconsciously, regulates how we think about formulating ways to achieve a given outcome. However, we do not live in a linear world and, more often than not, taking a linear approach almost guarantees catastrophic failure.

Failure is an implicit feature of complexity: the more complex a system, the more ways it can fail, whether it is the financial collapse of the stock market or the actions of a military unit that results in mission failure or casualties. The greater a system's complexity, the more important is the need to anticipate the various failure modes, bearing in mind that anticipating a failure mode is not the same as predicting its size or when and where it will occur. Therefore, along with the inevitability of failure comes uncertainty, and this too is a consequence of a system's complexity. What we interpret as failure is a qualitative change or more formally an emergent property in a system's complex dynamics. An unwanted property to be sure, but one that is unavoidable. The fact that it cannot be avoided does not mean that it can be predicted, at least not with the certainty of a deterministic process. Mathematics provides the cognitive tools necessary to systematically address questions that involve uncertainty, ambiguity, and paradox, often associated with failure. We are on the verge of a number of breakthroughs in CS, which require abandoning assumptions made in order to make classical analysis tractable. For example, the coupling across scales in dynamic systems described by renormalization group theory is on the verge of being replaced by the FC.[1] FC provides a formalism that enables one to incorporate the history of a process, as well as its nonlocality, into its dynamics, thereby being able to describe, for example, the nonperiodic dynamics of a spring that exceeds its elastic limit. Another is self-organized criticality in social phenomena necessary to explain consensus, or the transition of peaceful demonstrations into riots. These qualitative changes in dynamics also entail a different way to think about the underlying complexity.

If we cannot think systematically about a complex problem, we cannot solve it, and CS enhances the cognitive skills for solving problems critical to the military, a way of thinking made necessary by the demands of contemporary science to overcome the complexity barriers to understanding the modes of failure that are present in virtually every aspect of life and within every scientific discipline. CS has found its way into the US Army doctrine, for example, in the Training and Doctrine Command document *Win in a Complex World*, and the relatively new concept of Net-Centric Warfare.[2] The downside of these manifestations of CS within the Army entails the richness of nonlinear network dynamics, so that the scientific understanding of how phenomena fail must encompass both the qualitative and quantitative. To garner such understanding in a systematic way requires going beyond the traditional methods of modeling and simulation; that is, beyond using the classical analysis of analytic functions as the only ways of transforming data into information and subsequently into knowledge. Recent breakthroughs involve new methodologies within FC that generalize classical analytic functions to include the effects of memory and nonlocality by solving a fractional form of the Sturm-Liouville (SL) problem. We anticipate that just as solving the SL problem in the 19th century led to foundational insights into electricity and magnetism, kinetic theory, ultimately quantum mechanics, and in fact provided the mathematical backbone of modern physics. So too, the solution to the fractional SL problem will provide the foundational science necessary for solving today's multiscale problems of complexity in all the scientific disciplines crucial to the Army.

An alternative to the CS thinking is the misleading strategy of pushing natural variability from the central region of the probability density function (PDF), say from a Gauss distribution of potential outcomes out into the tails of the PDF. The ubiquitous, low-level variability, to which the processes could adapt, disappear from the policymaker's field of vision, making everything appear calm and trouble free. Consequently, when a fluctuation does appear, it is completely unexpected and devastating. The catastrophic consequence of such high-impact, low-probability events, results from complex systems becoming extremely fragile when their natural volatility is artificially suppressed to achieve short-term stability. Such controlled systems may not exhibit any visible signs of impending catastrophe prior to its occurrence, and so the traditional methods of anticipating failure breaks down.

A complex system has unforeseen consequences that occur at some substantial interval of time after the initial response is observed. It takes time for the activity to work its way through the various dynamic modes of a complex system and generate multiple emergent effects produced by local and global cooperation. Unfortunately, the attention of most people wanders after the initial reaction is observed, and they are surprised when a secondary, or even tertiary, reverberation disrupts simple expectations. Such unforeseen, but foreseeable, reactions can be sufficient to generate failure, which on the battlefield is potentially fatal. Army training in situational awareness will promote and develop CS thinking on the part of the warfighter to reduce the number of failures resulting from unanticipated outcomes or mistakes. A soon-to-be-published book[3] discusses the details along with visionary changes in future Army doctrine.

CS thinking abandons the linear paradigm and takes into account the reality that on the battlefield no 2 situations are ever exactly the same. For example, a situation may look the same as one previously encountered, but which of the system's many characteristic modes responds most strongly to a given stimulus changes from one encounter to the next? The change in response is a consequence of the many differences that were thought to be negligible or had gone unseen, which instead turn out to be crucial. Consequently, closely regulating the early response to a stimulus while it is still manageably small is crucial to understanding just how different the present situation is from what it was believed to be. Situational awareness is therefore not just seeing the "big picture", which it most certainly does, but perhaps even more importantly it includes an awareness of how the battlefield responds to an individual's actions and being keenly sensitive to any response that is new or at least unanticipated. The thing that is out of place, whatever does not belong on the physical or cyber battlespaces, is a warning of potential failure. Anything that is anomalous, which means it does not have an immediate explanation, is a signal to take cover, shut the system down, or at least to proceed with extra caution until the anomaly is understood and resolved.[3]

A significant example of the application of CS thinking is in the changing doctrine for conducting warfare in megacities.[4] In 2030 megacities will account for 60% of the world's population, 70% of the world's gross domestic product, and the urban environment will be the point of convergence for the drivers of instability. The scale of megacities defies the military's ability to apply historical methods of urban warfare, and consequently the Army's doctrinal and operational approaches will be shaped to incorporate CS. In 2050 these 37 international urban epicenters will have evolved into a connected network of economic hubs that drive the global economy as predicted. In most megacities, fragility will be the norm and the US military doctrine for urban warfare will have been modified to account for the sensitivity of the unique failure modes of a given megacity. For example, the operational understanding of how the disruption of a single subnetwork, such as transportation or food delivery, affects a given megacity as a whole. The CS theory of failure will enable the prediction of the network responses to military interventions into a megacity operation that is under an internal or external attack or digging out from under a natural disaster.

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List of Symbols, Abbreviations, and Acronyms

3-D	3-dimensional
AI	artificial intelligence
ALSMs	artificial layered semiconductor materials
ANNs	artificial neural networks
ARL	US Army Research Laboratory
ARO	Army Research Office
BLUF	bottom line up front
CRA	ARL Cyber Security Collaborative Research Alliance
CS	Complexity Science
DARPA	Defense Advanced Research Projects Agency
DL	deep learning
DOD	US Department of Defense
EM	electromagnetic(s)
FC	Fractional Calculus
IoT	Internet of Things
IR	infrared
Lidar	light detection and ranging
MIMO	multiple input and multiple output
ML	machine learning
MMWC	millimeter wave communications
NFEM	near-field electromagnetics
PDF	probability density function
PNT	positioning, navigation, and timing
QIS	Quantum Information Science
QO	quantum optics

R&D	research and development
S&T	science and technology
SL	Sturm-Liouville
SPP	surface plasmon polariton
ST	scientific and technology professional
SWaP-C	size, weight, power, and cost
TRL	Technology Readiness Level
UK	United Kingdom
UV	ultraviolet

1	DEFENSE TECHNICAL
(PDF)	INFORMATION CTR
	DTIC OCA
2	DIR ARL
(PDF)	IMAL HRA
	RECORDS MGMT
	RDRL DCL
	TECH LIB
1	GOVT PRINTG OFC
(PDF)	A MALHOTRA
1	ARL
(PDF)	RDRL-D
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