The Convergence of "Exciting" Technologies Between 2030 and 2040

U.S. ARMY WAR COLLEGE

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Class of 2021

About This Document

The Concept Squad prepared this document as an Integrated Research Project as partial requirement to complete the Master of Strategic Studies degree from the United States Army War College (USAWC). The research, analysis, and production of this product occurred over 30 weeks from October 2020 through April 2021 as part of the in-residence Army War College Senior Service College program. The results of this study were provided to Mr. Harry "Ed" Mornston, Director, Intelligence and Security, Army Futures Command. The team consists of two US Army Colonels (O-6), one Department of the Air Force Civilian (GS-15), one Department of the Army Civilian (GS-14), and one US Army Lieutenant Colonel: Johnny Casiano, William Snook, Gregory Lynch, Jo Dempsey, and Andy Pannier, respectively.

Requirement

What "exciting technologies"[1] will likely converge[2] in militarily relevant ways between 2030 and 2040 to challenge US interests at home and abroad?

This product was produced in multiple mediums, including a PDF (primary) and soft-bound book.

Figure 1: Exciting technologies will affect all sectors of government and industry. (Courtesy of Oilman Magazine)

Analytic Confidence

The analytic confidence of the Key Findings is moderate. Analytic confidence of each report is also indicated. The questions asked were complex and the timeline was relatively short due to competing academic requirements of the USAWC core curriculum. Source reliability and corroboration were moderate to high. The analysts (non-subject matter experts) worked both individually and collaboratively to answer the questions. They utilized a

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[1] **"Exciting"** technology incorporates developing, emerging, and surprising technologies in one term. **Developing**- Technologies undergoing growth or evolving which are part of current science and technology initiatives such as robotics, Artificial Intelligence (AI), Autonomous Systems (AS), and synthetic biology. **Emerging**- Technologies whose coming into being is not-yet fully understood or researched and have unfulfilled but promising potential. **Surprising-** Technology with a disparity between the amount of public and private fiscal investment and the amount of public interest it generates.

[2] Converge-The process of seemingly unrelated technologies connecting, forming an unexpected and complementary military capability.

combination of structured analytic techniques including nominal group technique and network analysis, among others. The team evaluated their analytic confidence utilizing Peterson's Analytic Confidence Factors coupled with the Friedman Corollaries (See Annex B).

Words of Estimative Probability

Analysts leveraged the Kesselman List of Estimative Words as their Words of Estimative Probability (WEP) (See Annex E) for determining the likelihood of a capability's convergence and challenged to US interests at home and abroad by 2030 to 2040.

Source Reliability

Source reliability is noted at the end of each citation as low (L), moderate (M), or high (H). The citation is hyperlinked to the source. Source reliability is determined using Standard Primary Source Credibility Scale (See Annex C) and the Trust Scale and Website Evaluation Worksheet (See Annex D).

Figure 2: Brain computer interface through optogenetics (Courtesy of Ready Laser)

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Key Findings

Out of the 171 technologies identified, 17 are highly likely "exciting" – technologies that are unknown or lesser known, militarily relevant, and developing or emerging. Each of these 17 technologies is highly likely to mature within the next ten years and may change the character of warfare in future conflicts and competition. Some of these technologies may be known within a research community and may not constitute a true surprise. However, they met the early evaluation criteria threshold, so they are included in the project for consideration. The 17 technologies are:

Figure 3: 17 Technologies included in project.

Amorphous Metals	Bio-Nano
Triboelectric Nanogenerators	Optogenetics
Light Bending Metamaterials	Exocortex
Digital Telepathy	Parallel Reality
Superhydrophobic Material	Microbiome
Carbon Nanotube Transistors	Neural Lace
Fully Homomorphic Encryption	4-D Printing
Photophoretic Volumetric Display	Electric Wood
Data Storage Glass	

Optogenetics

Optogenetics, the science of using light to control the behavior of neurons, is likely the top exciting technology and is highly likely to begin to emerge from the scientific community within three to five years. Currently, the limiting factor of optogenetics is the need to surgically implant devices into the human brain.

- Recent, rapid advances in optogenetics make it highly likely research institutes at Harvard, MIT, and Stanford, as well as several companies, such as RetroSense Theraputics, GenSight Biologics, and Weill Cornell Medical College will develop elementary wireless capabilities to control human thoughts over the next three to five years.

- To date, researchers at the University of Florida have successfully controlled the memories of mice and placed "false memories" into the brains of the mice, demonstrated the ability to control neurons in the brains of mice to switch off behavior that controls addiction, advanced the pace and effectiveness of cognitive skills training, and identified the precise brain circuits for hunger, thirst, breathing, memory, smell, hearing, seeing, and feeling.

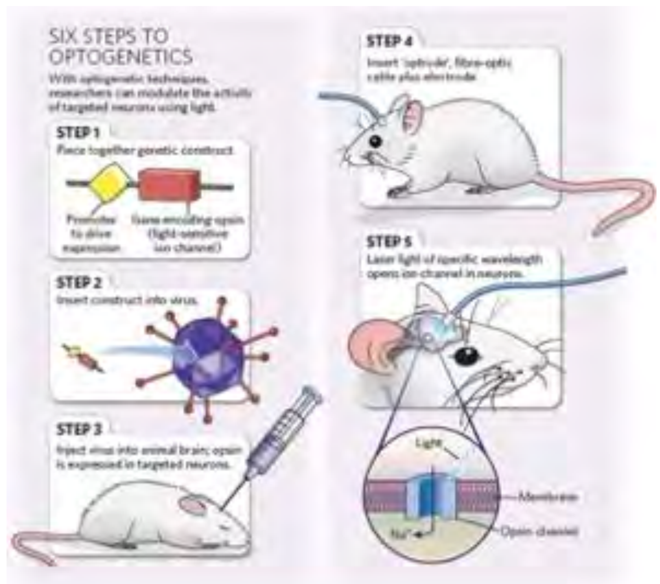

Figure 4: Optogenetics process (Courtesy of Weebly)

- While the United States is the leader in research on optogenetics, due to the constraint of FDA regulatory requirements for brain implants, the US is likely to fall behind China in use of optogenetic devices in humans within six to 12 years.

Triboelectric Nanogenerators

A triboelectric nanogenerator (TENG) is an energy harvesting device that converts external mechanical energy into electricity by a conjunction of triboelectric effect and electrostatic induction. TENGs are likely to be available for commercial scale production by 2027. Once they are produced at the industrial level, TENGs are highly likely to allow small electronic devices such as implants, wearables, and sensors for the internet of things to be powered from subtle friction that is currently not being capitalized on as a source of electricity. This could free users from dependence on batteries and other currently used recharge systems. The limiting factors to commercialization of TENGs are their durability, low energy output, and energy storage capacity.

- Much of the research conducted on TENGs originated in China. A research team from Xiamen University discovered the first TENG in 2012. These researchers demonstrated “a simple, low cost and effective approach of using the charging process in friction to convert mechanical energy into electric power for driving small electronics.”
- According to Business Wire, “The triboelectric nanogenerator market is expected to grow at a compound annual growth rate of 48.55% over the forecast period of 2019-2025 to reach a market size of $134.1 million in 2025 from $18.5 million in 2019.”

Figure 5: Skin-like triboelectric nanogenerator developed by a Chinese research team at National Center for Nanoscience and Technology in China. (Courtesy of PHYS.Org)

Bio-nano Processors

Bio-nano processors, which integrate living cells into semiconductor material and the reverse, integrating nanoelectric components into living cells, will highly likely enable new and exquisite functions while integrating into larger, more complex systems. The field involves merging nanotechnology, biotechnology, and computer science to create bio-nano processors to replicate cellular processes on a chip. The limiting factors of bio-nano processors revolve around ethical concerns, and physical challenges with production obstacles for scalability and manufacturing.

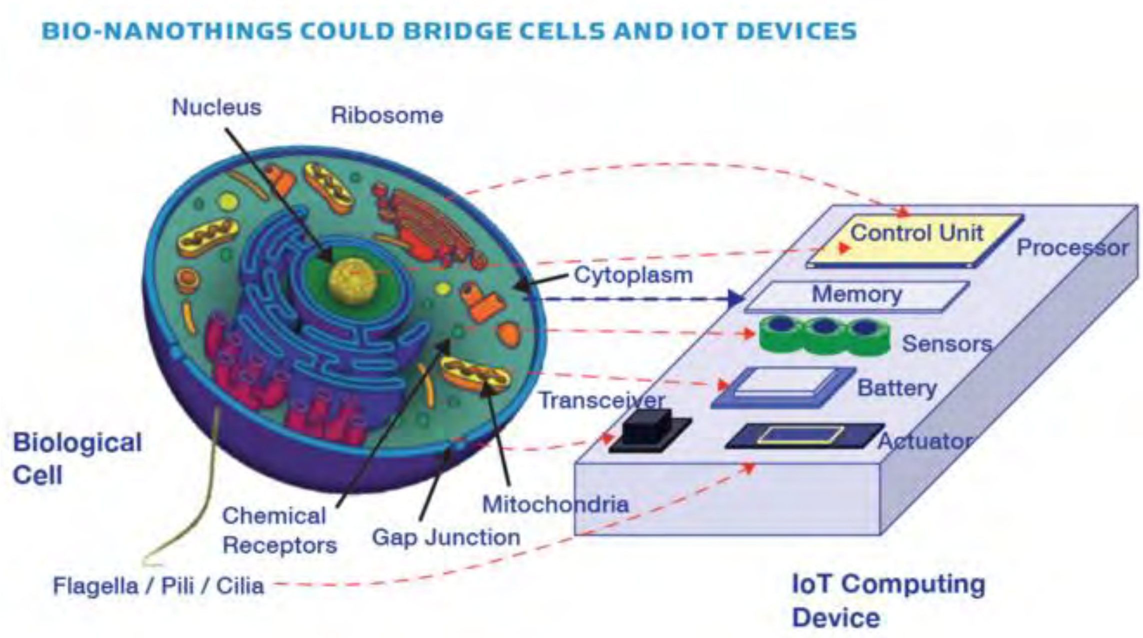

Figure 6: Bio-nanothings bridge cells and IOT devices. (Courtesy of Institute for the Future)

- Research into the bio-nano field includes numerous countries, with China, the US, and India publishing the most research on the topic.
- Top five funded companies conducting research into bio-nano systems include Oxford Nanopore Technologies, Nantero, Liquidia Technologies, DigiLens and Albionic. The five companies alone received over $200 million in funding in 2018 for medical and other applications across the spectrum.

Amorphous Metals

Widespread amorphous metals use is highly likely within 5 years with high Chinese interest, and military applications between 2025 and 2030. Research into amorphous metals, non-crystalline metals with glass-like structure, continues to widen potential application fields, develop new compositions of metallic alloys, and create novel processing routes. Potential application fields include structural materials, hydrogen storage materials, soft magnetic materials, and biomaterials. The limiting factors of amorphous metals are the complexities of working with the materials.

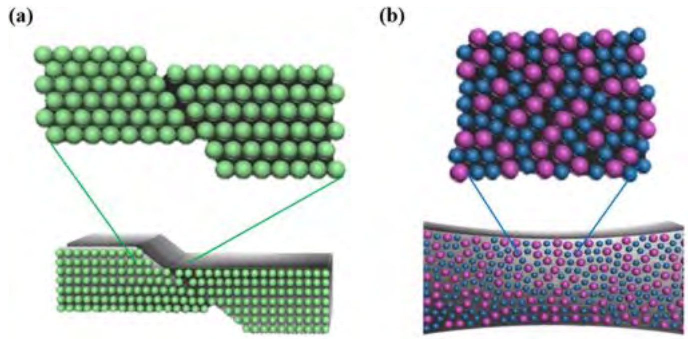

Figure 7: Comparison of crystalline (left) vs. amorphous material (right) which shows how the amorphous material bends and does not break. (Courtesy of Nature.com)

- Two Chinese technology companies, Shenzhen Amorphous Technology Co. Ltd. and WENERGY, are leading in the amorphous metal industry; one creates quieter, more energy efficient products used in 5G, transportation, and national defense security, while the other provides amorphous metal products such as transformer cores and electromagnetic interference (EMI) shielding materials for electronic devices to the military industry.

Neural Lace

Neural lace is an ultra-thin mesh that can be implanted in the skull, forming a unit of electrodes for monitoring brain function. It is likely to link human brains with computers without the need of a physical connection wired to the brain or body and allow for two-way communication. It is likely that neural lace will be used in humans between 2030 and 2040. Neural lace is an emerging technology in the field of Brain Computer Interface (BCI).

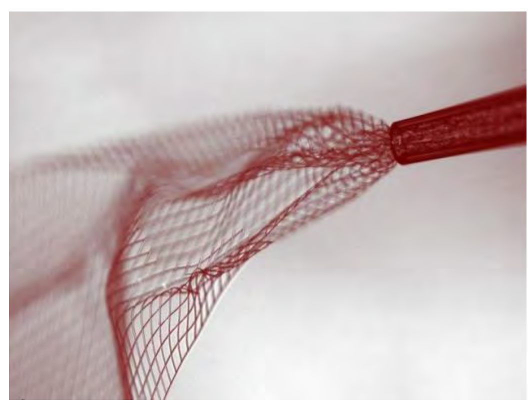

Figure 8: Rolled electronic mesh is injected through a glass needle into an aqueous solution. Courtesy of Lieber Research Group, Harvard University)

- In 2015 Dr. Charles Leiber and his team of scientists showed that mesh electronics with widths more than 30 times the needle diameter could be injected into the brain of a mouse and maintain a high yield of active electronic devices.
- Grand View Research predicts a compound annual growth rate of 15.50% during the period of 2020 to 2027.

Parallel Reality

Parallel reality technology will allow ubiquitous communication with hundreds or thousands of people who speak a diverse set of languages and understand cultural nuances differently simultaneously. It works by targeting the pixels on the display board, capable of simultaneously projecting up to millions of light rays of different colors and brightness. Each ray can then be software-directed to a specific person. Several companies will likely develop parallel reality technology in the next five years with widespread military use by 2030.

- Misapplied Sciences has at least 17 patents established for various aspects of the technology, ranging from multi-view displays, location dependent content, audio visual systems, wayfinding, and navigation displays. Delta Airlines has already tested this technology in select airports.

Figure 9: Thanks to Parallel Reality display technology, only the person on the left will see a personalized message onscreen. The person on the right will see something tailored to them. (Courtesy of New Atlas)

Light Bending Metamaterials

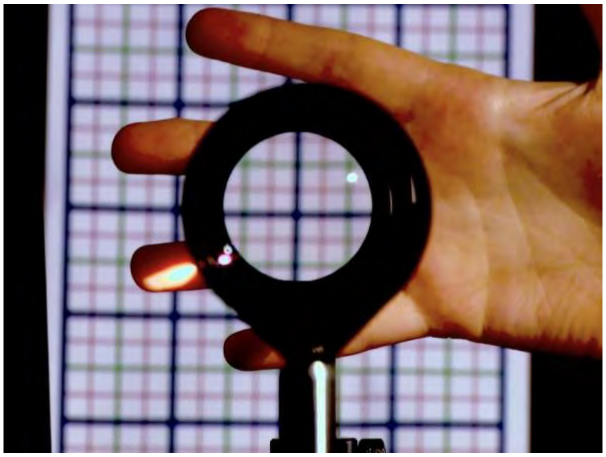

Figure 10: The ability to bend light around an object and show the background, incoming light from any angle and distance. (Courtesy of Forbes)

Light bending metamaterials are artificially structured materials used to control and manipulate a wide range of electromagnetic frequencies, including visible, infrared, and ultraviolet light. Regarding invisibility, metamaterial characteristics allow them to control the index of refraction to manipulate the path of light through an object. The light path instead bends around the object, making it invisible. Perfect light-bending metamaterial will likely appear across multiple industries in the next 10 years, with initial military use by 2035-2040.

- The greatest metamaterial research growth is outside the US, with 80% of publications coming from China since 2015. Breakthroughs are already making it into Chinese national security applications, such as hiding 3D objects in natural illumination for the entire spectrum of human eye sensitivity.

Superhydrophobic Materials

Superhydrophobic materials use a femtosecond laser for etching micro-and nano-scale patterns onto a structure's surface. Researchers using two aluminum pieces, created a structure in which the treated surfaces on two parallel aluminum plates face inward so they are enclosed and free from external wear and abrasion. This new structure creates "unsinkable" materials.

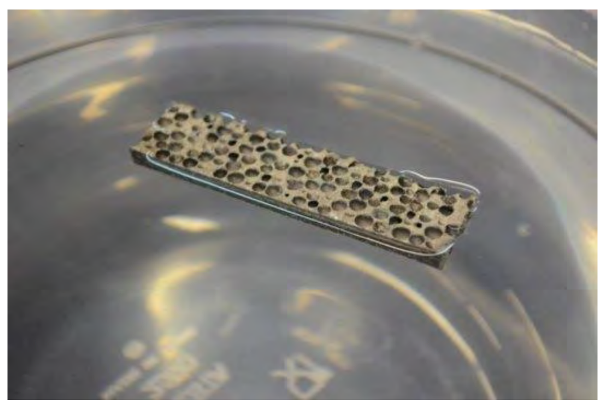

Figure 11: Floating unsinkable metal. (Courtesy of Bang Science)

- China will likely begin to produce naval vessels using this new superhydrophobic material within the next five to 10 years, due primarily to its shipbuilding capacity and demonstrated ability to bring technological innovations to market quickly.

Digital Telepathy

Digital telepathy is an applied research into BCI and Brain to Brain Interface (BtBI), augmented by various other current technological advances. Digital telepathy will likely allow humans to use limited digital telepathic communications in everyday life by 2030. The world's most advanced militaries will likely explore digital telepathy's initial use by 2035, with more pervasive use by 2040.

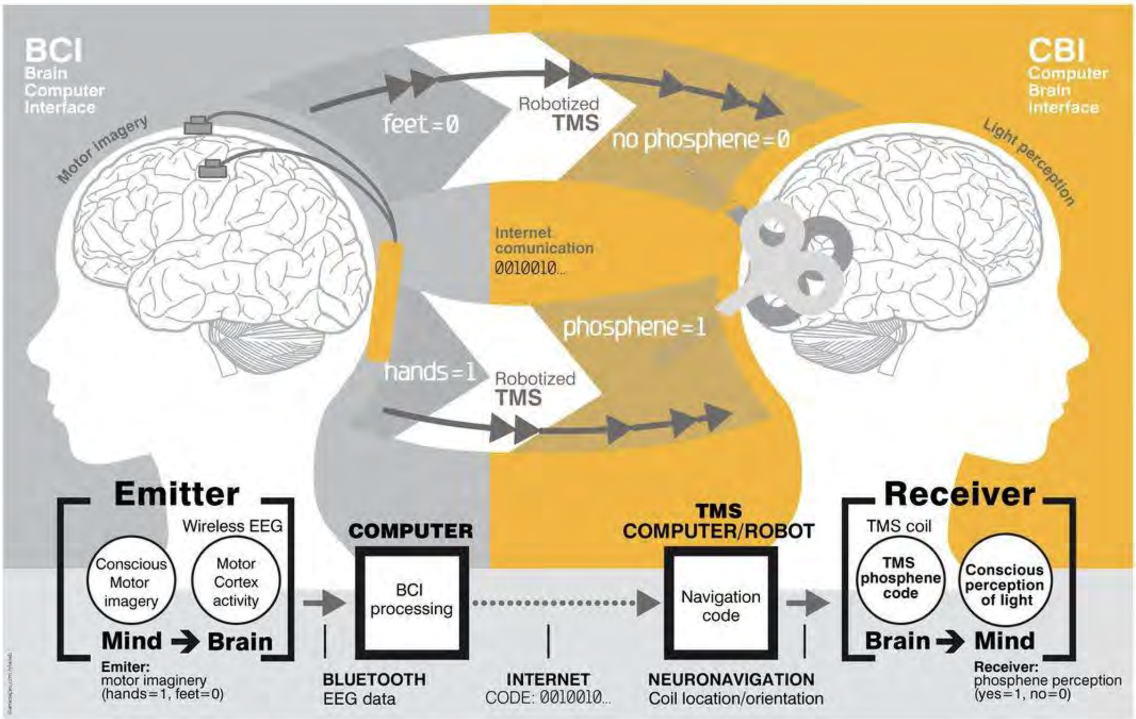

Figure 12: BCI technology. (Courtesy of Smithsonianmag.com)

- Tianjin University and the China Electronics Corporation have achieved breakthroughs in research on a BCI chip, known as "Brain Talker," specially designed to decode brainwave information.

Exocortex

An exocortex is an external computer that plugs into the human brain either wirelessly or through a physical BCI. Exocortexes are computers, used to augment high-level cognitive processes, and inform a user's decisions and actions. Once connected, the premise includes an increase in intellectual information and a larger memory. Exocortexes will likely begin around 2030 with widespread adoption by 2040.

- Organizations like the International Society for Military Ethics in Europe have provided an ethical stance on human enhancements like the exocortex. In a 2019 symposium, this organization provided the approval to conduct work in the development of human enhancements.

Figure 13: Exocortex. (Courtesy of Wikipedia)

4D Printing

Four-dimensional (4D) printing is the technology which allows traditional three-dimensional (3D) printed products to alter their shape when certain external stimuli are applied. 4D printing is essentially the same as 3D printing with the added element of the fourth dimension, time. 4D printed products have two elements instead of one, the rigid layered 3D structure (this is the product of 3D printing) and a geometrically coded flexible 3D structure. The products for 4D printing are printed on a 3D printer. 4-D printing is highly likely to reach commercial and military application by 2030.

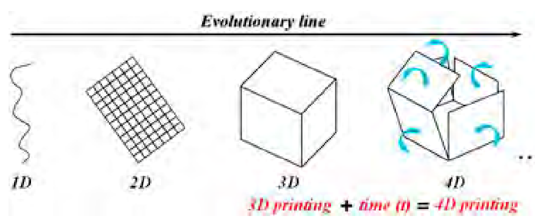

Figure 14: Schematic illustration of 1D, 2D, 3D, and 4D concepts. (Courtesy of Researchgate)

- Mordor Intelligence predicts that 4D printing growth will go from $62.02 million in 2020, to $488.02 million by 2026, at a combined annual growth rate of 41.96% over the forecast period (2021 - 2026).

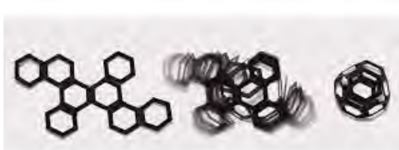

Figure 15: 4D printing. (Courtesy of ABB Group)

Data Storage Glass

Nanostructure glass stores large amounts of data in a small area for an extremely long period of time, with a high degree of stability. Data storage glass uses "five-dimensional" (5D) data storage and will provide an option for a long-term solution to large capacity storage. 5D applications currently use nanostructure glass and a femtosecond laser, the same laser used for LASIK eye surgery, to store approximately 360 terabytes of data, with a functionally limitless storage life. Data storage glass is likely to enter production for government, military, and large-scale corporate use by 2035.

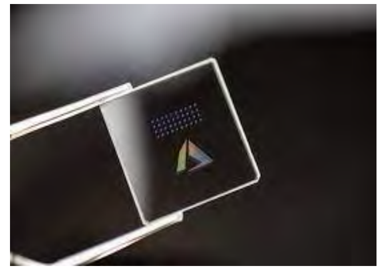

Figure 16: Data Storage Glass. (Courtesy of Microsoft)

- Russia is pursuing a 5D storage project at the Advanced Research Foundation and is working with advanced quartz to develop a long-term storage solution.

Electric Wood

"Electric Wood" includes wood products which conduct electricity or otherwise mimic other products traditionally found in electronics. Research into the use of wood products in technology continues to evolve, increasing the availability of biodegradable circuits, flexible circuits, conductors, and smart materials which can be used in drones, robotics, and communication devices. It is likely the use of "electric wood" will be widespread within 10 years and include military use by 2030.

- In Switzerland, an experiment demonstrated the feasibility of producing electricity from wood products, which could generate voltage to run low-power electronics.

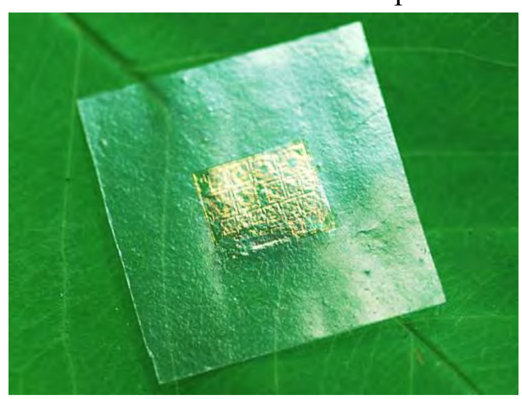

Figure 17: Green microchips created on cellulose nanofibril paper. (Courtesy of IEEE)

Photophoretic Trap Volumetric Display

Photophoretic trap volumetric display technology creates full-color, full motion, 3D graphics in thin air. This technology creates visual representations of objects in three dimensions, with an almost 360-degree spherical viewing angle in which the image changes as the viewer moves around. Recent discoveries into volumetric display technology will make it likely that 3D technology will start to dominate the commercial space over the next eight to 12 years with military use by 2035-2040.

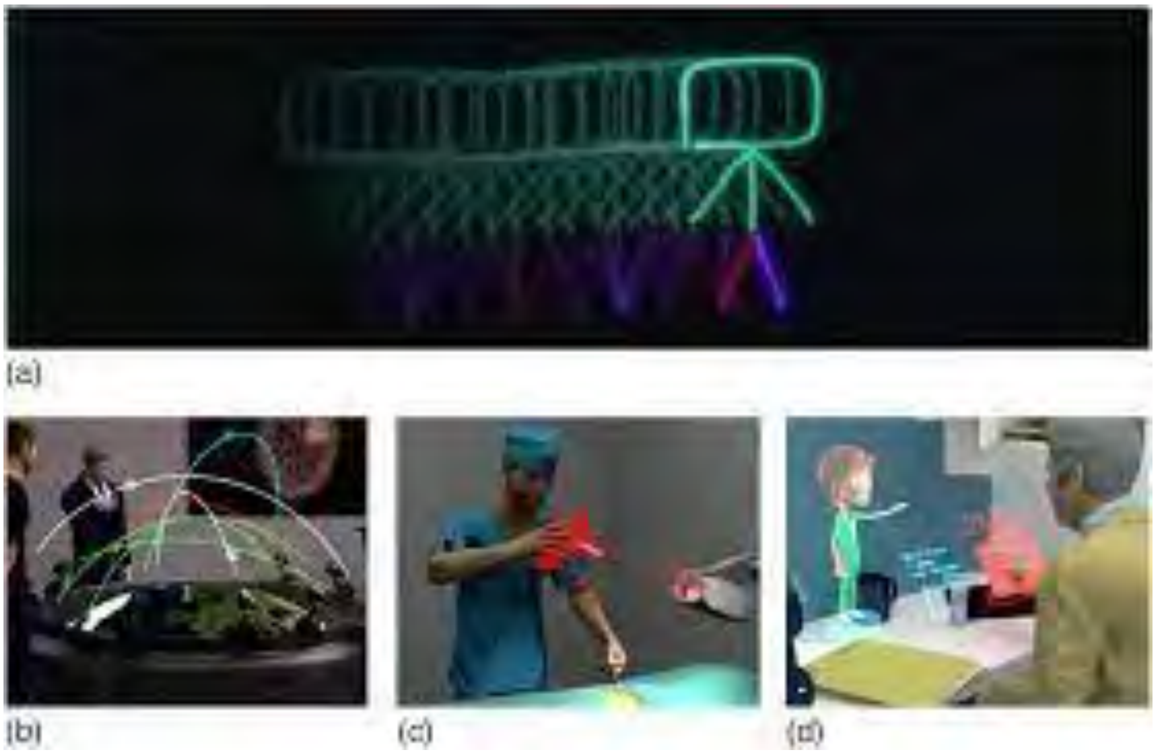

Figure 18: (Courtesy of National Science Foundation)

- According to Fior Markets, a technology research company, the current global market value of volumetric display technology is $217.6 million and will likely grow to an estimated $2.4 billion by 2025.

Fully Homomorphic Encryption

Fully homomorphic encryption (FHE) allows for the analysis or manipulation of data without decryption and without exposing the underlying data. FHE will likely quickly become the industry standard. FHE will likely provide an acceptable data protection level while balancing privacy with analytical capability. Because of the increased focus on securing data related to cloud computing, and the growing demand for shared and third-party data, FHE will likely become commercially available within 5 years.

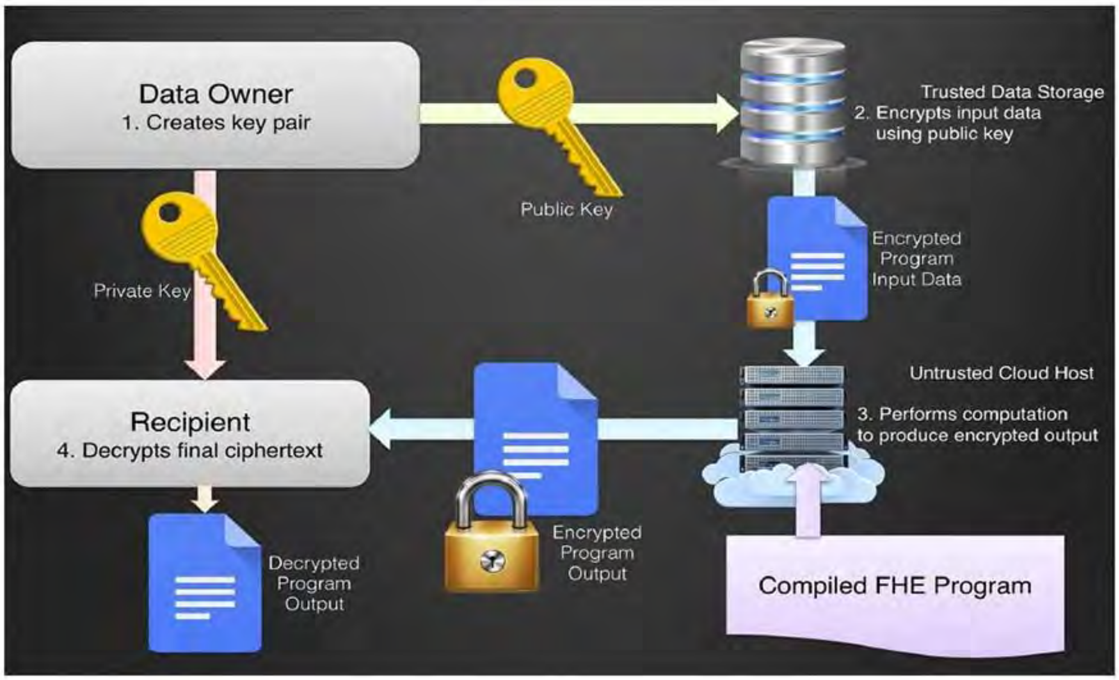

Figure 19: Evolution of fully homomorphic encryption. (Courtesy of Galois)

- According to Market Research Future, there will likely be significant growth in the homomorphic encryption field, with numbers generally showing growth of around 8.5% compound annual growth rate.

Microbiome

Microbiome research in 2020 identified how intestinal bacteria can affect the Central Nervous System (CNS) by communicating in a bidirectional network with signaling pathways called the gut-brain axis. Microbiome research will highly likely impact enhancement of Soldier health, optimizing the body's network, improving the interaction with sensors, and improving performance through probiotic augmentation, by the year 2025.

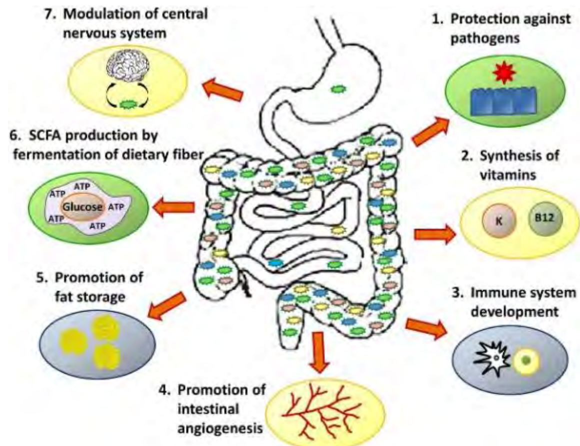

Figure 20: The human microbiome's role in homeostatic mechanisms in the body. (Courtesy of BMJ Journals)

- Global venture capital firm, SOSV, predicts the race to translate microbiome research into commercial therapies is under way with revenue expected to begin in 2021 and reach $10 billion by 2024, while continuing to steadily climb in the decade beyond.

Carbon Nanotube Transistors

Figure 21: Carbon nanotube transistors could lead to inexpensive, flexible electronics. (Courtesy of Phys.org)

Carbon nanotube transistors (CNTT) are transistors on the nanoscale used in radio transmissions and for communications. CNTTs are ultra-high strength, low-weight material, possessing highly conductive electrical and thermal properties. Due to recent breakthroughs in production techniques and product purity, it is highly likely that carbon nanotube technology (CNT) will be used in the radio and communications industry by 2025 and in military radio and communication platforms by 2030.

- In just the last two years researchers at the University of Southern California, Carbonics, Inc., and MIT have developed processes that can produce CNTs at commercial scales and that can compete in price with silicon computer chips.
- A novel approach taken by scientists in China uses single-strand DNA to produce scalable biogenerated CNTTs.

Military Relevance

While all 17 of these technologies qualify as "exciting," some are clearly more militarily relevant than others. Based on an analysis of three criteria, the time for the technology to materialize, how the technologies will likely converge, and which nation leads in research and development (US or a peer or near-peer nation), the most military relevant exciting technologies are:

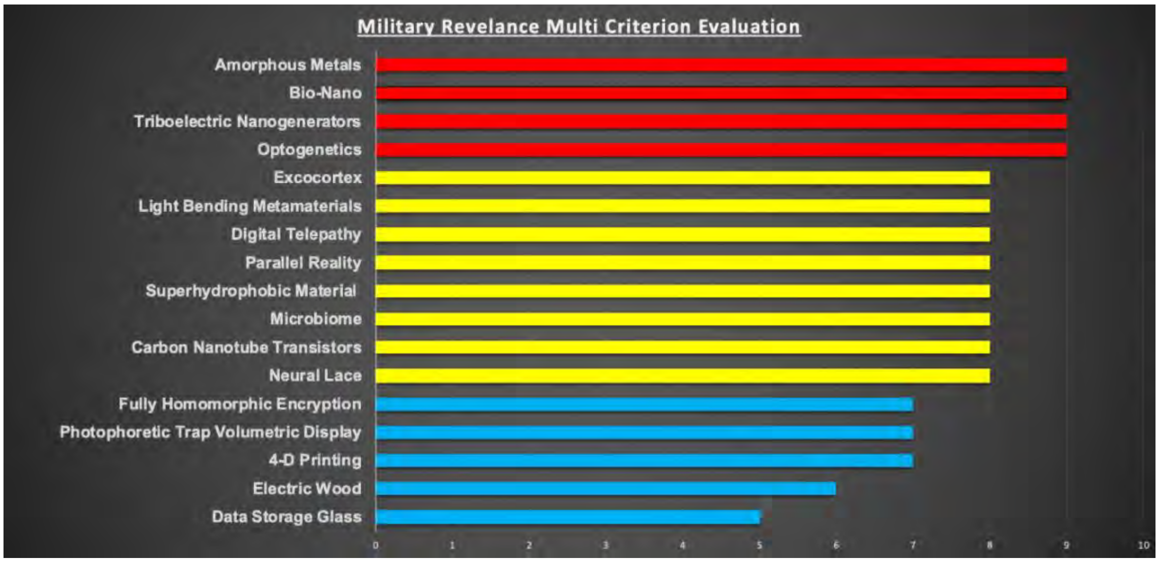

Figure 22: 17 technologies in order of military relevance. (Courtesy of Phys.org)

These 17 technologies are best partitioned into three tiers. Tier one technologies are, on average, likely to impact military development in the next five years, have minimal US government research, and are heavily invested in by peer or near peer competitors. Technologies in this category are optogenetics, triboelectric nanogenerators, bio-nano processors, and amorphous metals. Tier two technologies are, on average, likely to develop in five to 10 years, have minimal US government research and are moderately to heavily invested in by peer or near peer competitors. These technologies are exocortex, light bending metamaterials, digital telepathy, parallel reality, superhydrophobic material, microbiome, carbon nanotube transistors, and neural lace. Tier three technologies have a longer military development horizon, they are, on average, likely to mature in the 10–20-year cycle, have minimal to moderate US government research and are moderately invested in by peer or near peer competitors. These technologies are homomorphic encryption, photophoretic trap volumetric displays, 4D printing, electric wood, and data storage glass.

Technological convergence is difficult to define but is often identified as the trend or phenomenon where two or more technologies integrate to form a new outcome.[3] Many of

[3] https://www.everycrsreport.com/reports/R45746.html

the technologies in this report are still in early development and too conceptual to converge to produce a new outcome at this stage.

When examined as a network, however, all the technologies examined are likely to reinforce and augment each other in the future (see image below). There seemed to be a split between technologies as either enablers or beneficiaries. In general, enablers fall into categories such as materials and other basic technologies with wide applications across a number of products and industries. Beneficiaries are more complex and need support from many different disparate fields of study.

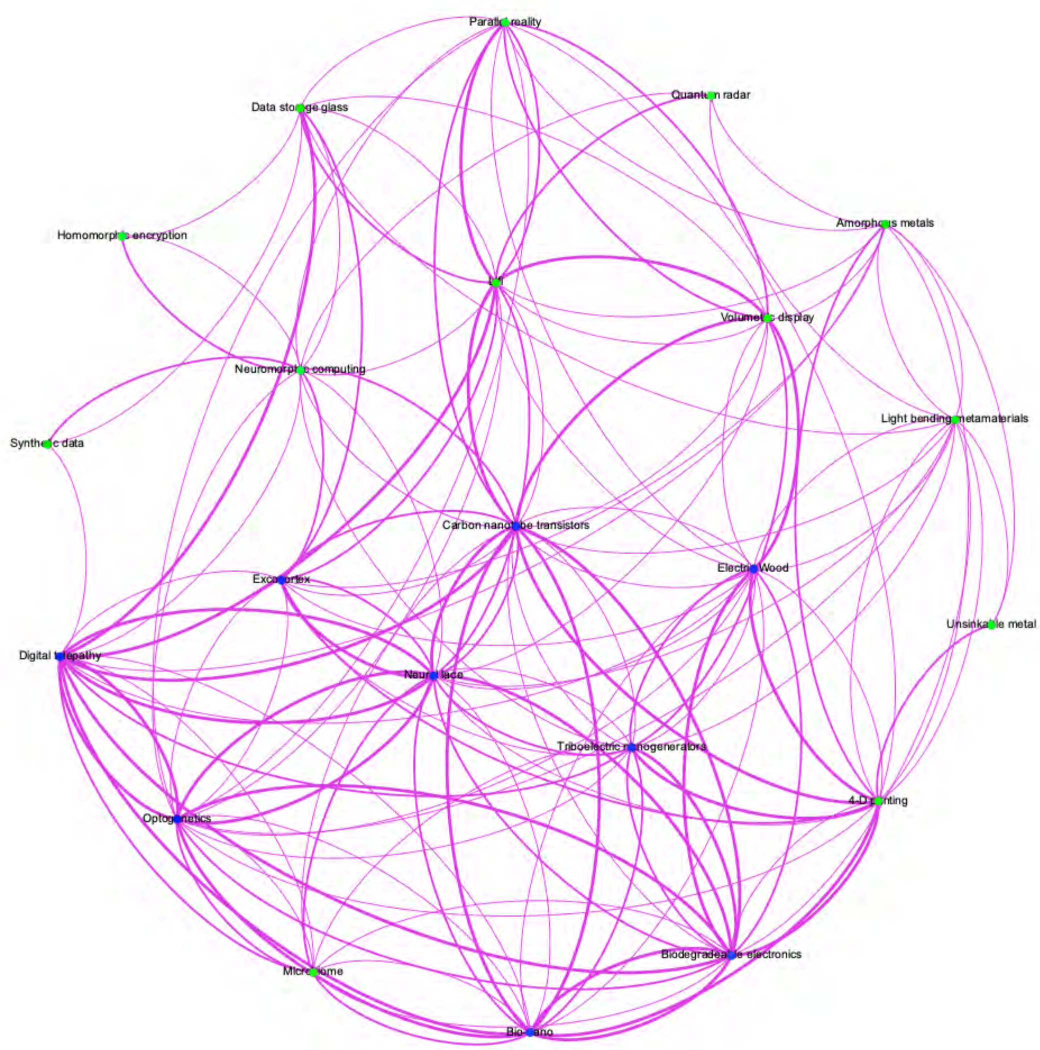

Figure 23: Network showing technological convergence with enabler nodes in green and beneficiary nodes in blue.

Beyond the network-centric categories of enablers and beneficiaries, two intuitive areas of likely convergence include brain to computer interfaces and the unique characteristics regarding light (or the control of light) as a communication (Li-Fi) or control device (optogenetics).

Additional Finding: Infrastructure

Convergence of many of these technologies will require at least four conditions to exist. The four conditions include a fully operational 6G technology, mastery of the terahertz (THz) regime of the electromagnetic spectrum, the prolongation of smaller, more powerful, and less expensive computing power, and overall cost-effectiveness. Those who wield the appropriate combination of elements will be the first to likely capitalize on technology in military relevant ways.

Table of Contents

Widespread Amorphous Metals Use Highly Likely Within 5 Years With High Chinese Interest, and Military Applications Between 2025–2030

Executive Summary

Rapid advances in processing techniques and developing compositions of amorphous metals make it highly likely widespread commercial and military applications will occur over the next five years with widespread military applications between 2025 and 2030. Despite the complexities of working with amorphous metals, the materials research and development continues to evolve due to its technological and scientific standing. Chinese interest in amorphous metals has increased over the last ten years as shown by the increase in the number of patents.

Discussion

Amorphous metals, also known as metallic glasses, have been around since 1960. The main difference between metals and amorphous metals comes from the rapid cooling of the material which allows the material to retain its non-crystalline or glasslike property.[H] (see figure 24) In 1976, metallic glass evolved to commercial use by the ability to create thin ribbons of material, which was used in distribution transformers.[H] Over the decades, the three main directions of research included new compositions of metallic alloys, novel processing routes, and potential application fields.[H] The potential application fields include structural materials, hydrogen storage materials, soft magnetic materials and biomaterials.[H] Amorphous metals may be used in medical instruments, military vehicles and aerospace industries.[H]

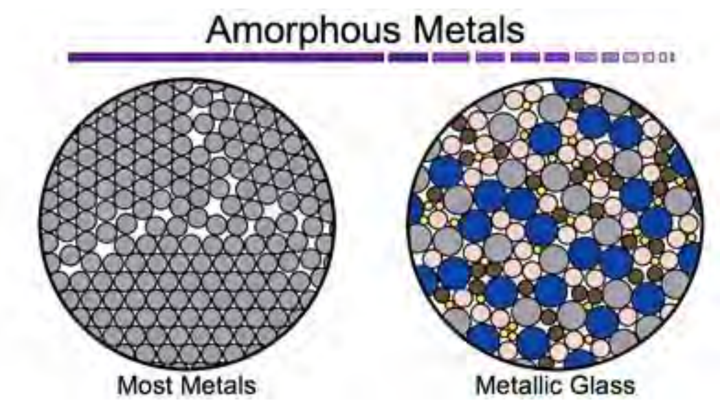

Figure 24: Amorphous Metals are also called Metallic Glass go to: https://www.youtube.com/watch?v=OhDb_jrQ7Ok to view video. (Picture Courtesy of Reade.com; Video courtesy of Youtube: Heraeus Group)

In 2018, Chih-Yuan Chen published a peer reviewed paper in which he analyzed patent bibliometric information on bulk metallic glasses (BMGs) in order to forecast the development trajectory as being in the growth stage from 2000-2015.[H] His research showed the highest number of patents originated in China from commercial businesses or research institutions.[H] Shenzhen Amorphous Technology Co. Ltd. in China creates amorphous ribbons which can be shaped into quieter, more energy efficient products used in 5G, transportation, and national defense security.[H] Another Chinese company, WENERGY, provides amorphous metal products such as transformer cores and electromagnetic interference (EMI) shielding materials for electronic devices to the military industry.[H] The company's website shows a picture of their Iranian friends who joined them during the China International Industry Fair (CIIF).[H]

Amorphous metals are attractive for use in the medical field for a variety of reasons to include being non-toxic, strong, hard, and corrosion and wear resistant, when implanted in the human body.[H] Heraeus Amloy business unit is researching implants made from biocompatible amorphous metals, and how they can be adapted to an individual's physique.[H] In 2017, Themis Kyriakides, PhD, created a glucose sensor from platinum-based BMGs, and estimates, within five years develop a sensor for clinical use.[H] In 2019, Jung et al. published a study on the use of amorphous metals for a multi-functional sensor in electronic skin. This skin tracks pressure, temperature, has an optical sensor and a microheater for injecting medicine which makes it useful in applications such as human-machine interactive interfaces, healthcare-monitoring systems, and medical diagnostic devices.[H]

Amorphous metals are twice as strong, weigh the same and are more resistant to corrosion and wear, as other metals, which makes them attractive for use in military armor.[H] (see figure 25) It can also disperse impact energy more effectively.[H] The US military is currently developing armor-piercing ammunition with this material.[H] Amorphous metals can provide a break-proof, lighter casing and electromagnetic interference (EMI) shielding properties.[H] EMI shielding in electronics can protect from a disruption of signals and extremely important capability in the military community.[H] Amorphous metals can also be used in the production of drones due to its unique properties.[H]

Figure 25: Amorphous Metals provide a metallic, glass like surface which is resistant to corrosion and wear. (Courtesy of LIFEBOAT.COM)

One way to expand the field of amorphous materials is to create BMG composites.[H] The development of using sulfur in amorphous materials continued the evolution towards a more processable medium which increases its commercialization.[H] In 2019, Heraeus, a technology group from Germany, fabricated the largest 3D printed gear wheel using amorphous metals.[H] In 2020, Chinese researchers developed a promising option for fabricating BMG composites using a 3D printing and forming process.[H] Defect vibrations in amorphous metals disrupt energy transfer and reduce heat conductivity, so research continues to reduce the inconsistencies of working with these types of material.[H] Despite the processing related complexities, novel ways of working with amorphous metals will almost certainly continue to evolve due to the materials technological and scientific standing.[M]

Analytic Confidence

The analytic confidence for this estimate is *high*. Sources were reliable and tended to corroborate one another. There was adequate time, but the analyst worked alone and did not use a structured method. This report is sensitive to change due to new information.

Bio-Nano Processors Likely Available Within 9 to 14 Years, Not Available For Commercial Use Until After 2040

Executive Summary

Bio-nano processors, which integrate living cells into semiconductor material and the reverse, integrating nanoelectric components into living cells, likely to enter production by 2030 to 2035 and will not be field-deployable until after 2040. The study involves merging nanotechnology, biotechnology, and computer science to create "bio-nano processors to replicate cellular processes on a chip. Most of the focus revolves around biomedicine. Still, companies and academic institutions are branching out and looking at unique ways to use bio-nano processors and components to support a diverse mission set ranging from space-based applications to secure network circuits. Ethical limits to bio-nano processors exist as well, presented as integrating computers into a human cell infrastructure as unethical and embarking on potentially dangerous practices. Additionally, the challenges associated with integrating bio-nano processors into networks, the cyber interface and communication methods are all challenges that still need solving before the technology is possible.

Discussion

Bio-nano processers have applications throughout the spectrum of medicine, but there are numerous applications outside of medicine on the horizon for the technology. Research is being conducted on nanoscale robots and extending brain-to-brain and brain-to-machine interfaces. Multiple technologies likely to converge in the next decade to bring the concepts to the demonstration phase.[M] The concept of a bio-nano space suit capable of responding to damage or failure and repairing itself is a concept discussed in the nano community.[L] The undetectable nature of nanotechnology makes it ideal as a weapon, or in the case of bio-nano, for enhancing the performance of soldiers.[M]

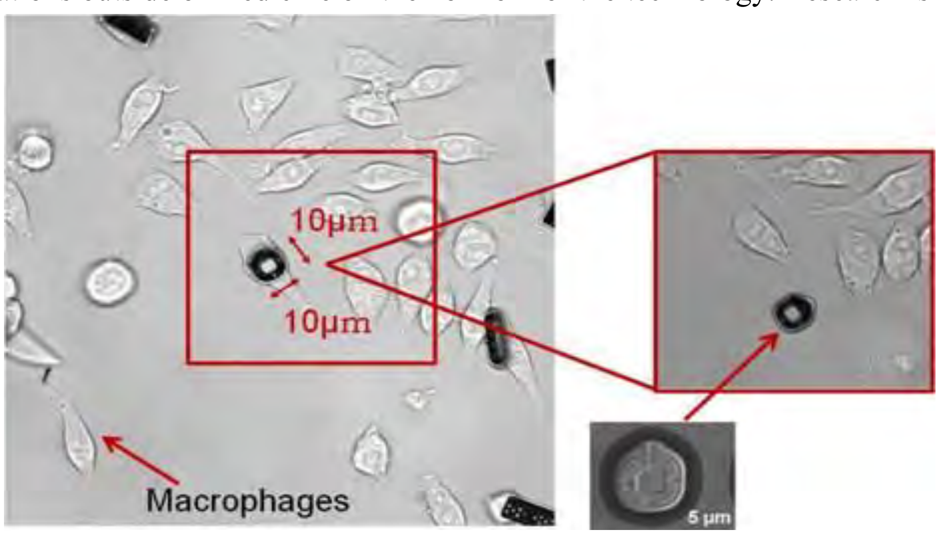

Figure 26: Chip in a cell. (Courtesy of Stanford University)

Companies are conducting research into bio-nano systems, including Oxford Nanopore Technologies, Nantero, Liquidia Technologies, DigiLens and Albionic. The five companies alone received over $200 million in funding in 2018 for medical and exquisite applications across the spectrum.[H] Numerous countries are researching the bio-nano field, with China, the US, and India publishing the most research on the topic.[M] NASA initiated a comprehensive study into bio-nano processors and components through Northwestern University to study protein and DNA configurations for use as bio-nano machine components.[M] Additionally, the team looked at light-weight networks containing millions of bio-nano-robotic elements for sensing and signaling capabilities to map and explore large planetary surfaces and astronaut "bio-nano gears" to protect them against harmful environments in space.[M] The Institute for Communication Technologies and Embedded Systems is partnering with RWTH Aachen University in Germany to field a Bio-nano electric logic locking system using a DNA "biological activation key," ensuring an attacker is not able to electronically access the targeted circuit or network.[M] A researcher at the Biohybrid Systems Laboratory, University of Tokyo, Collaborative Research Center for Bio/Nano Hybrid Process is researching how to make living cells as components to create processors, sensors, and actuators.[M]

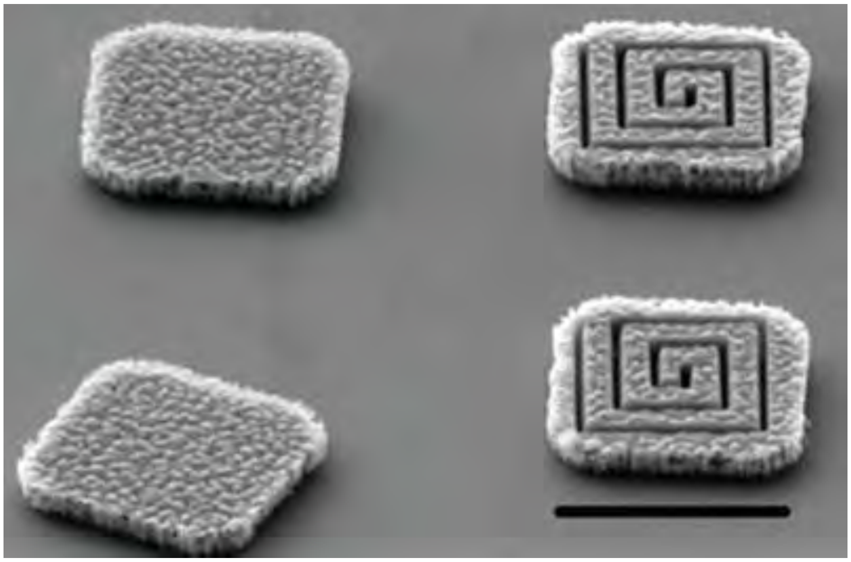

Figure 27: Scanning electron microscope before and after nanostructuring. (Courtesy of Nanowerk)

Bio-nano and nanotechnology present ethical and physical challenges for the future and production obstacles for scalability and manufacturing. Manipulating matter on the scale required is an obstacle and one of the most significant issues in developing nanosystems.[H] Some opponents of bio-nano and overall nanotechnologies are resistant to integrating machines into medicine and manipulating cells at the nano level.[M] Additionally, the ethical concern of possessing a "smart card" containing our entire DNA sequence or genome raises the issue of privacy and data protection.[M] The view or perspective is that humans may be crossing a natural boundary by installing computer chips or bio-nano processors in their bodies.[M] Additionally, researchers at Georgia Tech highlighted the new bio-nano organisms could become a threat to the host, and even act as a pathogen driving the need for a potential “kill switch” to neutralize the bio-nano device in the event something goes wrong.[M] Another obstacle is the challenge of communication with the nano devices and how to balance short, medium and long-range communications and how to map the molecular communications system.[M] Finally, the bio-cyber interface and the challenges associated with the bio-nano network is not solved yet and is a roadblock to realizing the potential of the concept.[M]

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were generally credible and did not demonstrate any bias. The analyst did collaborate with team members and did not use a structured method. The topic matter was somewhat complex, but the research was basic and straightforward, and there were some time constraints on the assessment. Based on the speed and priority of the development, there is likely to be new information available in the foreseeable future. An update is not anticipated.

Triboelectric Nanogenerators Likely to Reach Commercial Production by 2027

Executive Summary

Triboelectric nanogenerator (TENGs) which allow electric charges to be created from friction and static are likely to be available for commercial scale production by 2027. Once they are produced at the industrial level, TENGs are highly likely to allow small electronic devices such as implants, wearables, and sensors for the internet of things to be powered from subtle friction that is not being capitalized on as a source of electricity. This could free users from dependence on batteries and other currently used recharge systems. The limiting factors to commercialization of TENGs are their durability, low energy output, and energy storage capacity. As evidenced in the sources of this paper, much of the research conducted on TENGs originated in China.

Discussion

There are three types of nanogenerators[4] currently recognized: triboelectric[5], piezoelectric[6], and pyroelectric[7].H Triboelectric and piezoelectric nanogenerators use small scale mechanical energy to produce electricity. H This paper focuses on triboelectric nanogenerators (TENGs). A research team from Xiamen University, China discovered the first TENGs in 2012.H These researchers demonstrated "a simple, low cost and effective approach of using the charging process in friction to convert mechanical energy into electric power for driving small electronics." H Since then, researchers identified four established modes for TENGs (see figure 28): contact-separation mode, sliding mode, single-electrode mode, and freestanding mode.H One of the aspects that makes triboelectric nanogenerators so appealing are the many sources from which the

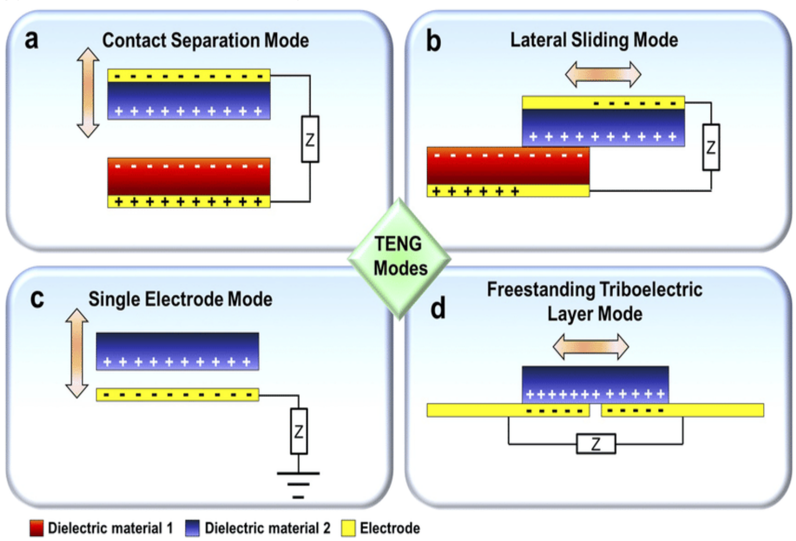

Figure 28: Four modes of triboelectric generators. (Courtesy of Sungkyunkwan University)

[4] Nanogenerator – converts small scale amounts of thermal or mechanical energy into electricity
[5] Triboelectric – electricity produced by mechanical friction
[6] Piezoelectric – often associated with energy generated from shearing or heat and pressure
[7] Pyro-electric – generate temporary electricity when certain materials are heated

mechanical energy derives: human body movement, the rotation of tires on vehicles, wind, or wave motion to name a few.[H]

With so many possibilities for the mechanical energy source, researchers pursued many paths. A research team from China, led by Wencong He developed a method to increase the charge output by creating a shielding layer that prevents air breakdown and promotes charge accumlation.[H] Another research team from China developed a process to harvest energy more efficiently from low flutter (wind) velocity, such as a light breeze.[H] Until recently, research on TENGs largely centered around alternating current (AC) power generation, which then required it to be converted to direct current (DC) power and constant power for many technology-based electronics.[H] More recently, some researchers shifted their focus to the production of a constant current DC power from TENGs, this eliminated the need for conversion and energy storage as devices are powered directly from TENGs.[H] Research is also advancing along the lines of the source of the friction. In addition to wind, mentioned earlier, researchers are studying blue energy, ocean waves. In 2017, three Chinese researchers conducted a thorough review of the research conducted on wave energy and TENGs.[H] Their work highlights that TENGs are more effective at harvesting low frequency energy, than the currently used electromagnetic generators (EMG).[H] A more recent review of TENGs using wave energy highlighted

Figure 29: Illustration of TENG harvesting wind. (Courtesy of Xin Chen, Xiaojing Mu, and Ya Yang). To view click on the photo.

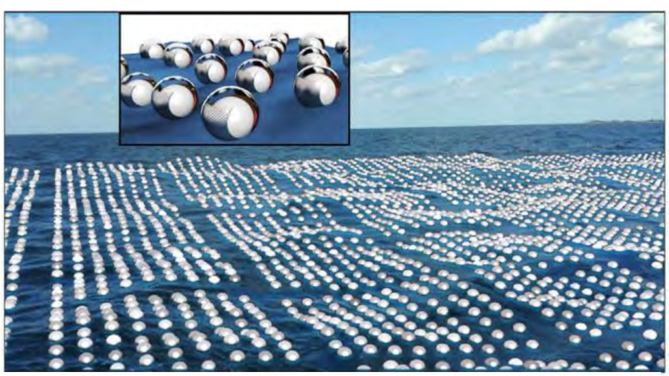

Figure 30: A proposed TENG network of balls harvesting ocean wave energy. (Courtesy of Zhong Wang, Tao Jiang, and Liang Xu).

research on TENG networks (see figure 30) to harvest energy in greater quantities and hybrid nanogenerators that combine TENGs with EMGs.[H]

The blue energy TENGs are likely to be used amongst marine and naval forces as energy harvesters, but there are also applications to land based uses. TENGs have been designed to produce electrical energy from simple human body movement, such as walking,[H] and from the rotation of wheels mounted on vehicles.[H] These applications are likely to free

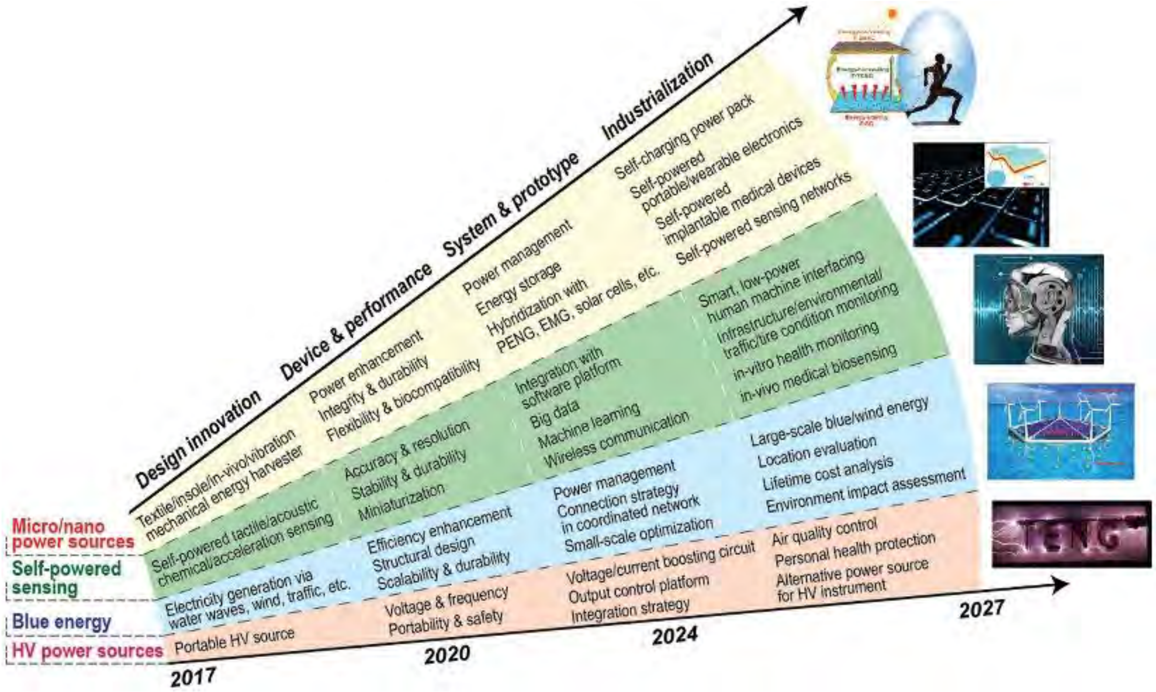

Figure 31: A timeline of TENG development. (Courtesy of Wiley-VCH).

militaries from dependence on batteries and fossil fuel-based recharge systems. Other highly likely applications across the military are self-powered, autonomous sensors and implantable electronics,[H] electronic skin,[H] and soft robotics[8] and machines.[H]

Though there are many advantages to TENGs such as low cost, high conversion efficiency, and ease of fabrication,[H] there are limitations to producing TENGs on a commercial scale. TENGs have low durability and high impedance.[H] Research was recently conducted to offset the durability issue with self-healing TENGs,[H] but it is still early in the research phase. Additional limitations, that must be researched further, are contact electrification, improving output energy, finding biodegradable materials, and effective energy storage.[H] TENGs are likely to be available for commercial scale production by 2027 (see figure 31).[H] "The triboelectric nanogenerator market is expected

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[8] "Soft robots and machines can be considered as soft systems that aim to use highly compliant materials with elastic moduli that are comparable to soft biological materials and human tissues" [H]

to grow at a compound annual growth rate of 48.55% over the forecast period of 2019-2025 to reach a market size of $134.119 million in 2025 from $18.543 million in 2019."[M]

Analytic Confidence

The analytic confidence for this estimate is *high*. Most sources were highly reliable and very closely aligned with one another's analysis, notably as the research spanned the last decade. The analyst worked alone and did not use a structured method. However, the analyst did confer with the team regarding TENGs rating as a surprise technology. There was adequate time to process the information. It is not likely that new information will change this estimate.

Mind Control Through the Use of Optogenetics Highly Likely Within 3-5 Years

Executive Summary

It is highly likely that human application of optogenetics in controlled research occurs within three to five years. Recent, rapid advances in optogenetics, the science of using light to control the behavior of cells, and the desire to further improve devices to emit light and non-invasive means of virus delivery make it highly likely that multiple research institutes and several companies, such as RetroSense Theraputics, GenSight Biologics, and Weill Cornell Medical College will develop wireless capabilities to control human thoughts over the next three to five years. However, there are still limitations to the effectiveness of light penetration into the brain and the invasive nature of overcoming this with the insertion of fiber optics. Research continues into less invasive means to stimulate the brain, alternate approaches to using light, and genetic modification to increase specificity of the targeting of cells. This requirement for further research and FDA approvals will keep optogenetics out of the public's hands until at least 2030.

Discussion

According to Scientifica, "Optogenetics is the science of combining genetic and optical methods to exert control over targeted cells within living tissue.[M] This control can be milli-second precise and cell type specific.[M] It allows deeper analysis of biological systems through the precise manipulation of electrical and biochemical activity within individual cells without disturbing wider processes in the tissue or organism."[M] See the process of optogenetics in figure 32. Optogenetics arrived on the research scene in 2005, when Dr. Deisseroth demonstrated neurons response to light stimulation.[M] Using optogenetics,

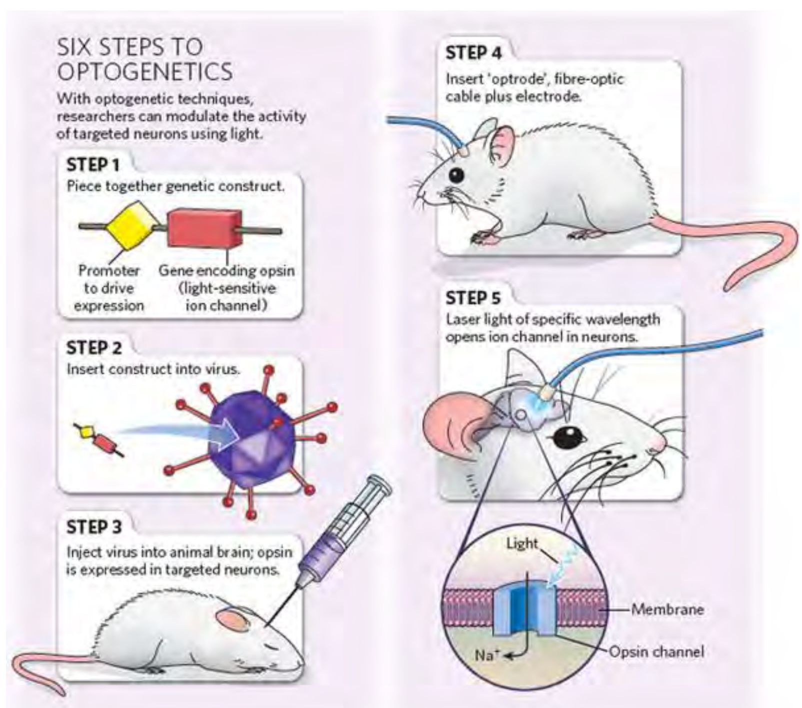

Figure 32: Optogenetics process. (Courtesy of Weebly).

scientists target specific space at specific times in order to effect specific cell types.[M] Using optogenetics, from 2012 to 2014, multiple researchers successfully controlled the memories of mice and placed "false memories" into the brains of the mice (see figure 2).[H] Other research shown the ability to control neurons in the brains of mice to switch off behavior that controls cocaine addiction.[M] Still other research demonstrated the use of optogenetics to evoke hallucinations.[H] Through the University of Florida, Defense Advanced Research Projects Agency (DARPA) pursued research using optogenetics in rodents to advance pace and effectiveness of cognitive skills training.[H] Through thousands of experiments, scientists used optogenetics to "identify the precise brain circuits for hunger, thirst, breathing, remembering, smelling, hearing, seeing, feeling, and hearing, and more."[M]

The application of genetic engineering occurs through the introduction of viruses carrying specific genetic codes that are introduced into the brain.[H] There are limitations to the success of this engineering, particularly in the efficiency and specificity of various opsins used to stimulate and inhibit neuron activity.[H] Another challenge of optogenetics is the invasive delivery of light sources, such as fiber optics inside the brain of live animals due to limited tissue penetration of photons.[H] Researchers attempt to overcome this challenge by application of various strategies. One strategy involves intracranial injection of nanoparticles, these nanoparticles absorb near-infrared light and transform it into blue light in the brain of the subject.[H] This allows for deeper tissue penetration, than the traditional blue laser light used in most optogenetics techniques.[H] According to a research team at Stanford, led by Xiang Wu, "Despite these advances, these methods either require partial removal of scalp and skull to afford deeper penetration or involve intracranial delivery of photoluminescent agents into deep brain tissue."[H] A technique being developed for a wireless approach to control the brain activity is to replace direct light illumination with focused ultrasound (FUS), which affords much deeper penetration in biological tissues including the brain and replace intracranial delivery of the light source.[H] Chinese scientists have recently developed microscale light-emitting diodes (micro-LEDs), which can be wirelessly operated, serve as injectable light sources that directly interact with neural systems.[H] Researchers in

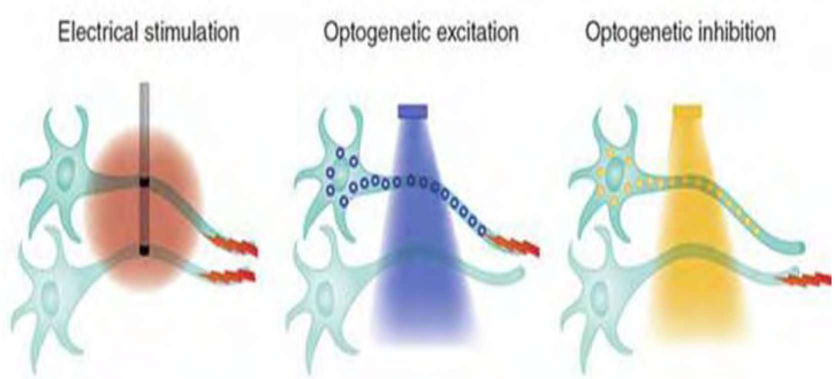

Figure 33: Harvard researchers demonstrated that optogenetics, unlike electrical impulses can selectively control memory pathways. (Courtesy of Dr. Karl Deisseroth)

Japan dispensed with the optical fibers that the original optogenetics needs to carry light to brain neurons, they simply shined light onto lab mice's skulls.[H]

In efforts to move from rodent to human testing, in August 2015, RetroSense Theraputics received FDA approval for human trials of their optogenetics-based therapy to treat blindness due to retinitis pigmentosa and advanced dry age-related macular degeneration.[M] RetroSense was bought out by Allegan in 2016. Since then, Allergan has pursued the gene therapy but only to the eye, not the brain.[M]

Optogenetics technology continues to progress for applications with humans as researchers pursue wireless means to administer the light portion of optogenetics and use novel viruses to further enhance introduction of the genetic material. GenSight Biologics of Paris and Bionic Sight, a startup out of Weill Cornell Medical College, both say a combination of wearable electronics and gene therapy has a chance to restore vision by re-creating the retina's ability to sense light.[M] They have developed a pair of goggles that can administer images and the light source for optogenetics.[M] The invasive nature of optogenetics remains one of the main reasons it has not progressed quicker in moving from lab animals to human research and FDA approval. This has caused some researchers to move away from the light portion of mind control and look for other sources such as acoustics and chemogenetics.[M]

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were reliable and tended to corroborate one another. There was adequate time, but the analyst worked alone and did not use a structured method. Furthermore, given the lengthy period of the estimate, this report is sensitive to change due to new information.

Exocortex Will Likely See Military Application Between 2030 and 2040

Executive Summary

Despite still being mostly theoretical, use of exocortexes--computers used to augment high-level cognitive processes and inform a user's decisions and actions--will likely begin around 2030 with widespread adoption by 2040. The exocortex could be wearable or implanted and will likely go through several variations before society accepts a suitable version. Work on wearable tech and the significant work going into brain computer interface technology are encouraging signs of approaching success. Ethical hurdles are also an issue with this technology that are already being looked at and discussed in government circles.

Discussion

Humans have been using exocortexes arguably for hundreds of years. The idea of shifting work from the human brain or augmenting the human brain goes back arguably to even before the pencil and paper. The rudimentary devices of paper and pencil are intelligence- and memory-boosting technologies like an exocortex of the future.[L] Science fiction has been writing about this technology since at least the 1980s, and scientific theory on augmenting human intelligence with the support of technology has been around since the 1950s.[M] You can even see the concept of an exocortex in video games such as HALO. (see figure 34)

Figure 34: (Courtesy of HALO Official Site)

The human mind can only maintain so much information, and devices like the ones mentioned above and others like calculators and computers all play a similar role in providing an intelligence-or memory-boosting technology for humans. In 1956 George A. Miller, a founding father of cognitive psychology put forward a theory that most adults can store between five and nine items in their short-term memory.[M] He called it the magic number seven. He thought that short term memory could hold seven (plus or minus two items) because it only had a certain number of “slots” in which items could be stored. This theory has been used since and is why today phone numbers are seven digits and why an exocortex would be useful for humans.

Figure 35: Patient with amputated arms is moving a robotic arm with his thoughts. The modular robotic prosthesis was developed by the Johns Hopkins University Applied Physics Laboratory (APL). (Courtesy of BCI Early Success)

What precisely an exocortex will look like has limited source material currently written about it.[L] The first step towards developing an exocortex is to solve the BCI challenge. A BCI will have likely have numerous roles or functions moving into the future.[M] One of the early successes of this technology is using a BCI to enable artificial limbs for amputee patients.[M] Medical science has progressed far enough forward that today this technology is successfully in use. Other industries are also looking at BCIs. The gaming industry and military industrial complex have also moved into this space to work on BCI technology. Today, the BCI market leaders are Natus Medical, Mind Solutions, Compudemics, Emotiv Incorporation, and Neurosky.[M] Market analysis by tech firm Grandview Research demonstrates that BCI is a growing market with the market valued at $1.2 billion in 2019 and is anticipated to register a compound annual growth rate of 15.5% between now and 2027.[M] This indicator makes it highly likely that BCIs will be widely used by 2030 setting the stage for exocortex technology.

What makes an exocortex different than a set of augmented glasses is the glasses, or any other similar technology is an external device to the brain. Working on a computer to type a report or search for relevant information to complete the report is external. These devices act as components that people use and must interpret. An exocortex would be very different.[L] The premise behind an exocortex is to not feel as if a computer has been strapped on to the brain like another computer, but once connected to have an increase in intellectual information and a larger memory.[L] In short, the computer and person come together to produce a hybrid intellect.[M] When the brain and computer process unit (CPU) come together, the person feels like their usual self with all their memories but has access to a massive volume of information.[L]

Figure 36: "Human Enhancement and the Consequences of Change." (Courtesy of NLGreene)

Ethical concerns abound as the human mind and computer world slam together. Who would be able to use cognitive enhancement technology? How would humans make sure the technology feeding into our minds stayed private and secure? Enhancing human intelligence is a complex and challenging endeavor. Organizations like the International Society for Military Ethics in Europe have already started to discuss and provide an ethical stance on human enhancements like the exocortex. In a symposium in 2019 this organization provided the approval to conduct work in the development of human enhancements.[M] Not all countries will put this level of scrutiny behind their decision-making when it comes to human enhancements like exocortexes. However, with large, influential democratic countries building an international norm for using such technology, it will likely make the commercialization of such products like exocortexes accessible into mainstream development and use. Based on this research, it is likely that exocortex use will be in place by 2035.[L]

Analytic Confidence

The analytic confidence for this estimate is *low*. Sources were generally reliable but were not of high academic standing. Many of the sources had different views or names for similar technology that further impacted the analytic confidence. There was adequate time, but the analyst worked alone and did not use a structured method. Furthermore, given the estimate's limited time frame, this report is sensitive to change due to breakthroughs and new information.

Perfect Light-bending Metamaterial Likely in 10 Years; Initial Military Use Between 2035-2040

Executive Summary

Perfect light-bending metamaterial, that can alter oncoming light's path, making objects appear invisible, will likely appear across multiple industries in the next ten years, with initial military use between 2035-2040. Over the last five years, a disproportionately higher quantity of research about this technology has come out of China. Because the technology currently does not simultaneously manipulate all wavelengths of light traveling through it, industry primes may balk at its immediate practical application. Still, the explosion of new research into metamaterials will likely drive the adoption cycle.

Discussion

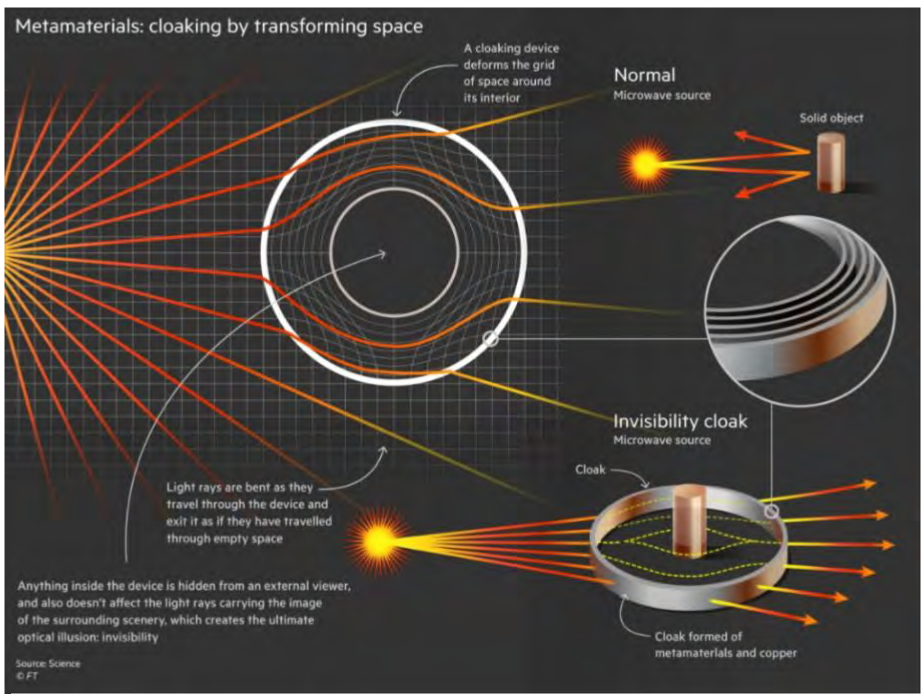

Figure 37: Picture depicting metamaterial bending the oncoming light's path hiding anything inside the cloaking device from external view. (Courtesy of Financial Times Science Report)

Metamaterials are artificially structured materials used to control and manipulate light, sound, and many other physical phenomena.[H] Their properties are derived from both inherent properties of their constituent materials, as well as from the geometrical arrangement of those materials.[H] Regarding invisibility, metamaterial characteristics[9] allow them to control the index of refraction[10] to manipulate the path of light through an object. The light path instead bends around the object, making it invisible (see figure 37).

[9] Metamaterial characteristics consist of periodically or randomly distributed artificial structures that have a size and spacing much smaller than the wavelengths of incoming electromagnetic radiation.[H]

[10] Index of Refraction is the measurement of a light ray bending when passing from one medium into another.[H]

This phenomenon produces a negative index of refraction, something previously believed to be impossible in the world of optics.[H] With these metamaterials advancements, the idea of a long-standing fantastical invisibility cloak has become more tangible.[H]

To appreciate the timeline regarding perfect light-bending metamaterial technology, a review of the 2010 Cheshire Jet research project written by then Major Timothy E. Beers at the Air Command and Staff College is necessary. He aptly uses the back casting method to layout a reasonable adoption timeline, including the goal, the path, the obstacles, and the milestones to developing this technology. From 2010–14, Generation One categorizes the development process as specific use and narrow frequency bandwidth, on the order of 250,000 GHz. This iteration will be centered around the near-infrared (IR) radiation band and cover about a quarter of the IR spectrum.[H] The subsequent five to 15 years, 2015–24, will be categorized as Generation Two: limited use but with a bandwidth approaching the entire optical frequency range, roughly 300 to 3,000 THz. This achievement will require several tunable materials working in concert. Cloaking will still be imperfect but more effective over a wider environmental range.[H] The last 15-25 years, 2025–34, will be categorized as Generation Three: wide use and broadband frequency range from IR to ultraviolet (UV) provided by a single, though layered, active material. Cloaking will be perfected, thus achieving optical stealth (invisibility) in most environments. These materials will be integral to aircraft design and function as both skin and structure.[H]

Representing Major Beers' Generation Two, in 2017, Northwestern University researchers developed a first-of-its-kind technique for creating entirely new classes of optical materials and devices that will likely lead to light bending and cloaking devices.[H] Using DNA as a key tool, the interdisciplinary team took gold nanoparticles of different sizes and shapes and arranged them in two and three dimensions to form optically active superlattices.[H] The result led to programmable structures that may shift to any desired point on the visible color spectrum.[M] This new technique represents a way not just to bend the light, but block it, bounce it back, basically make it do whatever you want, so long as the nanoparticles belong to something adaptable with DNA (like gold).[M] Additionally, the DNA strands are sensitive to environmental stimuli, meaning they modulate by adding certain chemical compounds that prompt them to contract or expand.[M] The change in DNA length resulted in a shift in color from black to red to green, providing extreme optical tunability.[H]

Sir John Pendry of London's Imperial College is a metamaterials pioneer.[H] In a recent interview, he suggested that China has been early into the game of metamaterials and has a flourishing school of researchers.[H] The greatest metamaterial research growth is outside the US, with 80% of publications coming from China since 2015.[H] Breakthroughs are already making it into Chinese national security applications.[H] For example, in 2018, several Chinese scientists from the National Natural Science Foundation of China set out to invent a "real device that can hide an object from sight in visible light from absolutely any viewpoint."[H] At the culmination of their research, their work provided a new solution for hiding a 3D object in natural illumination for the entire spectrum of human eye sensitivity.[H] Adding that it will have practical applications in surveillance technology for security and defense-related purposes.[H]

Both the US and Chinese advancements associated with this technology have kept pace with Major Beers' 2010 back casting methodology. The global metamaterials market will likely to grow from $448.0 million in 2018 to $1.8 billion by 2023, with further growth to $5.9 billion by 2028.[H] Speaking in 2018, Duke University Metamaterial expert Professor Smith said this is potentially the first large market scale big play that metamaterials technology has had.[H] There are four new major companies and three additional in incubation, all focusing their efforts on metamaterial development for various industries.[H] One company has raised more than $200M, with investors including Bill Gates. [H]

Despite the technical difficulties of building a metamaterial that manipulates all wavelengths of light in physical form, Chinese researchers may have discovered a solution. A team from Southeast University in Nanjing, China, has combined the best of metamaterials with information technologies to create a digital material – the first so-called Digital Coding Metamaterial (DCM). [M] The team has used the concept to control the DCM's response to specific electromagnetic wavelengths such as the microwave frequencies, terahertz radiation, and the acoustic spectrum. Still, the new materials will, over time, become even more interesting when they are used to simultaneously manipulate multiple electromagnetic wavelength ranges all at once, which will let them achieve multiple physical responses at the same time.[M] This also speaks to Major Beers' Generation Three: single, though layered, active material and integral to design and function as both skin and structure. Other barriers include bulkiness[H] and malleability of the metamaterials. However, each year, scientists improve upon metamaterials' technology.[H] UC San Diego engineers, for example, developed a cloak less than an inch thick.[H]

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were highly credible, and most did not demonstrate any bias. The analyst worked alone and did not use a structured method. The subject is very complex, and there was adequate time to comprehend the information. There is likely to be new information available in the foreseeable future, and the estimate is subject to change.

Digital Telepathy Likely in 10 Years; Initial Military Use by 2035

Executive Summary

Applied research into BC and Brain to Brain Interface (BtBI), augmented by the various other current technological advances, will make it likely that humans will use limited digital telepathic communications in everyday life by 2030. The world's most advanced militaries will explore digital telepathy's initial use by 2035, with more pervasive use by 2040. The current BtBI studies are not without challenges. Brain interfaces are not yet sophisticated enough to carry a lot of data and the technical hardware is unwieldy. Still, the increase and ease of digital connectivity across society in the coming decade, the introduction of the Internet of Senses (IoS), and the convenience of silently communicating at range, will drive the adoption cycle.

Discussion

Figure 38: Thomas Oxley (Neurosurgeon and Founder/CEO of Synchron) describes neural interface tech to enable telepathy. (Courtesy of Synchromed) To view click on the photo.

In five short years (from 2015 to 2020), experts in the digital telepathy field have gone from referencing this technology as something for the distant future to it being likely to surface commercially in the next decade. BCI and BtBI use a neural-interface device to facilitate the data transfer between a human brain and a computer. There are three characteristics of a neural-interface device necessary for digital telepathy to occur. The device must sense, compute and control; sense brain activity, compute brain data through a machine-learning artificial intelligence algorithm and control the sending and receiving of a message. (see figure 38)[H]

With exponential improvements in the areas of machine learning (ML), AI, a ubiquitous IoS powered by 5G,[M] and neural-dust type sensors (the recently patented stentrobe, for example[M]), it is practicable to imagine the proliferation of telepathic capability. At Ericsson Research, their vision is that advanced technology will enable a full internet of senses by 2025, and include the ability to digitally communicate thoughts by 2030.[M] Dr. Eric Leuthardt, a neurosurgeon at Washington University in St. Louis stated, "it's not inconceivable to think that within a 20-year time frame everything in your cell phone could be put into a grain of rice."[M] Consolidating the hardware and software elements of

a smart device into something as small as a grain of rice and non-invasively meshing it with human biology is likely to offer numerous military applications.
Answering the United States' brain science program, China has commenced several programs to counter the traditional US dominance in maintaining a technological advantage on the battlefield.[M] In the last two years, the PRC has invested heavy government and corporate sector resources into digital telepathy research, development, testing, and evaluation (RDT&E). [H] Chinese scientists claimed to have developed a human brain-computer interface to send targeting information directly to a search-and-rescue drone.[H]

The China Brain Project, which boasts BtBI capability by 2030, has the involvement of the Academy of Military Medical Sciences (AMMS), the renowned Chinese Research Institute.[M] AMMS' participation is distinctly significant because it indicates the pursuit of military application. As commanders' cognitive demands must become more acute on the future battlefield, new directions in integrating human and machine intelligence will likely prove militarily advantageous.[M] Wu Haitao, a researcher with AMMS, has suggested, "a brain-to-brain collaborative combat platform would optimize battlefield perception and maximize combat links to command effectiveness to capture fleeting opportunities and achieve unexpected victories."[M] Separately, Tianjin University and the China Electronics Corporation have achieved breakthroughs in research on a BCI chip, known as "Brain Talker," specially designed to decode brainwave information. The advantages of this chip include its size, precision, efficiency in decoding information, and increased capability for fast communication, all of which can contribute to the realization of BCI technologies [for military purposes].[M]

US leadership envisions direct neural enhancement of the human brain for two-way data transfer.[M] "In a theater, you can have two people talking to each other without even whispering a word," says Hamid Krim, program manager for the Army Research Office.[H] Digital telepathy is poised to assimilate perfectly into the Multi-Domain Sensor Systems (MDSS) currently being developed by the US Army. As the Future Operating Environment (OE) compresses decision space and time and overwhelms one's ability to process, exploit and disseminate (PED) information[11], digital telepathy will enhance commanders' abilities to quickly obtain situational understanding and transmit directives across a network in near-real-time. The obvious next step is to discern how digital telepathy can augment MDSS. Over the next five years, the US will put $6.25 million into a program that separates brain signals that influence actions from those that manifest behaviors.[M] Several prominent universities have signed onto the program, including the University of Southern California, University of California Los Angeles, University of

[11] Dwight DuQuesnay and Andrew Valdez, Initial Capabilities Document for Multi-Domain Sensing Systems, Army Futures Command (AFC) (Austin, Texas, February 24, 2020), memorandum for distribution.

California Berkely, Duke University, and New York University. With US allies in mind, several UK universities are also involved.[M]

This technology will satisfy heavy commercial interest, particularly companies tied to the nascent Internet of Senses (IoS), making it likely that digital telepathy will become part of everyday life in the next decade. Along with the European Union, the US and China have put hundreds of millions of dollars into the technology's RDT&E with similar amounts invested for the future.[H] The current market value of BCI is $1.3 billion and is poised to reach $3.85 billion by 2027.[H] It stands to reason with industry breakthroughs and military interest in this technology, coupled with commercial demand for the IoS, the market value is likely to increase exponentially by 2030.

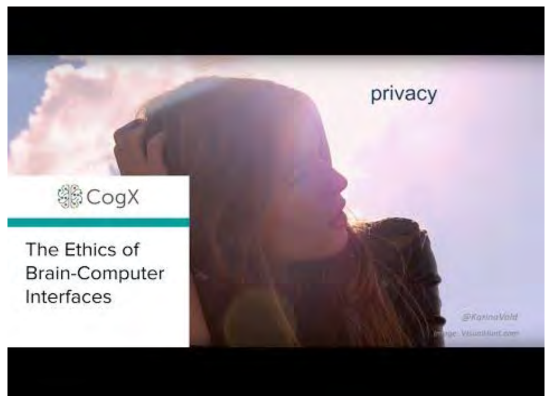

Figure 39: Dr. Karina Vold (Ph.D. at Cambridge University) discusses the ethics of BCIs. (Courtesy of CogX) To view click on the photo.

Digital telepathy is likely to face both ethical and technological hurdles. Whether it is an invasion of privacy or something more nefarious, such as the misuse of information for malign activity, unfettered access to someone else's brain could bring about culpability issues for a person's autonomy and responsibility. Another ethical dilemma is shared responsibility for thought or action. If the interconnectivity of multiple brains exists, how could one tell from where the process came?[H] Karina Vold, Ph.D. at the Leverhulme Centre for the Future of Intelligence, Cambridge University, suggests that appropriate securities will be in place before these technologies reach the consumer market, implying that they would develop alongside the growing use for military purposes (see figure 39).[H] Equally concerning is the level of information complexity transmitting data between participants. Scientists can only achieve a modest level of information transmission between participants and the low bit rate transmission requires a disproportionate amount of technical hardware.[H] Further, current studies are isolated to a server designed for the program.[H] However, with the introduction of non-invasive BCI devices[M] and a cloud based BtBI server to foster interactions between brains on a global scale,[H] science is likely to progress toward limited digital telepathy in the next decade.

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were reliable and tended to corroborate one another, except for one that cited a timeframe of 2050. There was adequate time to synthesize this information, but the analyst worked alone and did not use a structured method. The priority placed on this technology by leading governments and institutions - alongside the estimate's lengthy timeframe - will likely change this report due to breakthroughs and new information.

Parallel Reality Technology Likely by 2028; Military Use by 2030

Executive Summary

Several companies, including Misapplied Sciences, Samsung, and LG, will likely develop parallel reality technology[12], where one screen shows different things to different viewers at the same time, by 2028, with military use by 2030. The technology already exists with a blue-chip company beta testing it in the United States. Despite the heightened privacy implications with this technology, the proliferation of ubiquitous digital connectivity in society will likely drive the adoption cycle.

Discussion

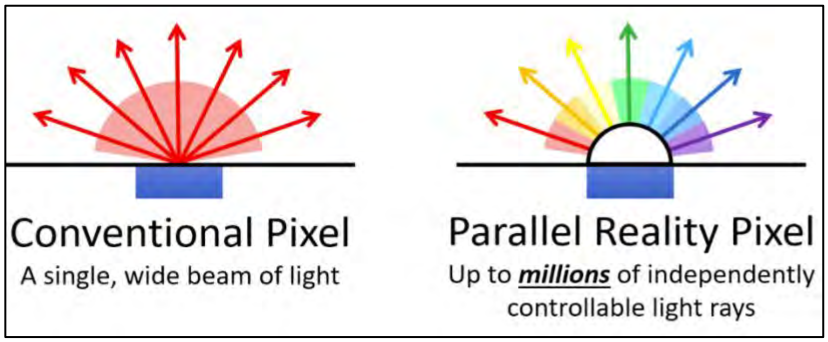

Figure 40: Picture from Misapplied Sciences' website depicting conventional pixels emitting a single color on the visible light spectrum and the parallel reality pixels emitting all colors simultaneously. (Courtesy of Misapplied Sciences)

Prompt and accurate information will facilitate efficient control at traditionally chaotic venues, like airports, sporting events, or theme parks. Communicating with hundreds or thousands of people who speak a diverse set of languages and understand cultural nuances differently simultaneously through one source increases efficiencies and reduces frustrations. This action underpins the idea behind parallel reality technology, developed by the Seattle, Washington start-up, Misapplied Sciences. It works by targeting the pixels on the display board, capable of simultaneously projecting up to millions of light rays of different colors and brightness (see figure 40). Each ray can then be software-directed to a specific person. Some pixels will be targeted toward one person, while other pixels will target another person.[M]

When combined with location technology and sensors, similar to those already embedded in a smartphone, the company says this content can be targeted in real-time from public displays to specific locations, people, and objects, essentially following them in three-dimensional space as they move through the world.[H] It works with the naked eye; no bulky headset or high-tech goggles required. And no need to bury your head in a smartphone for personalized information.[H]

[12] Parallel Reality Technology is when one screen shows different things to different viewers at the same time.

Misapplied Sciences has at least seventeen patents established for various aspects of the technology ranging from multi-view displays to location dependent content to audio-visual systems to wayfinding and navigation displays.[H]

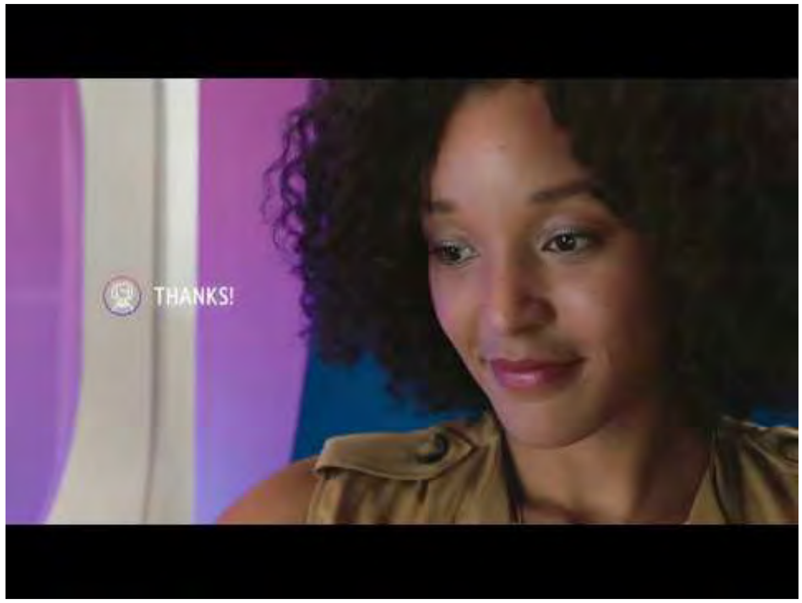

Figure 41: A Delta short describing the parallel reality technology Detroit International Airport will beta test in mid-2020. (Courtesy of Delta Airlines) To view click on the photo.

Uses for the technology seem endless, particularly as the human population continues to rely on digital feedback to navigate the world in which it lives. Kelly Tremblay, a Seattle-based clinician and neuroscientist who focuses on hearing loss among aging adults, suggests that society could benefit immensely from the technology, especially if it becomes scalable enough and affordable enough for different venues across different populations.[H] Delta Air Lines has announced that it will be testing the new technology to streamline and personalize the airport experience.[M] When a participating passenger walks past the display screen, it will present information including flight information, boarding details, directions to the gate, and more, all in their preselected language of choice (see figure 41).[H] Another participating passenger walking by at the same time will see their info, and not what the other passenger is seeing.[M] Moreover, imagine a commute to work or to visit extended family in the next town over from where you live. On the road, traffic signals are targeted individually to your car and other vehicles as they move — showing you a red light when you will not make the intersection in time and displaying a green light to another driver who can make it through safely. Still, another example considers fans at a stadium; the scoreboard displays their favorite players' stats. Fans nearby, each looking simultaneously at the same screen, instead see their favorites and other content customized to them.[H]

This technology will satisfy heavy commercial interest, particularly in advertising, offline content display, and lawful control of information, like the airport and traffic examples. Beyond some of the apparent benefits, such as retail brands better reaching relevant customers, this kind of offline personalization can have a more significant impact, such as subtitles always being in the language of choice or content always being legible based on distance, angle, and sightline. The opportunities are vast and have the potential to revolutionize a society currently dominated by smartphones and personal screens to a much wider world.[H] Search and personalization services, leveraging data and AI to personalize at scale, continue to be a significant area of investment among enterprises, both to make products and services more discoverable (and used) by customers, and to help business' own workers get their jobs done. The market is estimated to be worth some $100 billion annually.[H] Additionally, the military will likely use this technology in a host of ways, including professional military education with numerous students attending class and studying various discrete topics simultaneously; monitoring battlefield actions in a tactical operations center where the commander, S3 and S2 must all review something different tied to the same mission; or simply creating easy to follow directions around a large installation for a new army family.

Among the few barriers Parallel Reality Technology is likely to face during its adoption cycle, this tech's privacy implications will be the biggest hurdle. Issues such as fake news, targeted advertising, and native advertising[13], plague the technology.[M] Since parallel reality customizes peoples' experiences in the physical world, the technology relies on physical surveillance,[H] through a digital device. Resultingly, nefarious actors could spread different information to different people in alarming ways. These actions can solidify the disparities between people with different politics, values, interests, and beliefs.[H] In a world already struggling with digital tracking and "alternative facts," the ethical and privacy implications of parallel reality technology could be significant. How will we agree on a shared reality or a common set of facts when we can look at the same screen and see something different?[H] To assuage fears, Misapplied Sciences has advocated for opt-in advertising, as well as anonymized tracking of an individual's physical location. The upside of this technology's potential does not have to be consumed by its potential dangers.[H] One other concern with the technology is the company's ability to scale up production. With only four employees, Misapplied Sciences is seeking talented individuals to assist in bringing their product to market, advertising to recruit mathematicians, engineers, and software developers.[H] This biggest indicator to a scale problem is the company's desire to hire a mechanical and production engineer. [H] However, Delta Airlines made an equity investment in Misapplied Sciences in 2019,[H] and they are the first to embrace this groundbreaking Parallel Reality Technology, having dedicated the vision, brand, and resources to help bring it to market. They will not be the last.[M]

[13] Native Advertising is material in an online publication that resembles the publication's editorial content but is paid for by an advertiser and intended to promote its product.[M]

Analytic Confidence

The analytic confidence for this estimate is *moderate*. There were limited sources, but they were reliable and corroborated one another to include the technology's potential problems. There was adequate time to synthesize this information, but the analyst worked alone and did not use a structured method. The beta test with Delta Airlines suggests a priority within an isolated industry. However, success will facilitate a foothold in like industries. Given the beta test and timeframe for the technology to become adopted, new information will likely change the estimate.

China Likely to Use "Unsinkable Metal" to Build Naval Vessels Within 10 Years

Executive Summary

Due primarily to its shipbuilding capacity and its demonstrated ability to bring technological innovations to market quickly, China will likely begin to produce naval vessels using a new etching process that creates superhydrophobic or "unsinkable" metals within the next 10 years. Despite US Army funding for the research and other challenges associated with bringing a new technology like this to market, direct Chinese involvement with the study coupled with China's substantial shipbuilding capacity and its focus on naval modernization make it likely that the Chinese government will exploit the new technology and begin to incorporate it into its vessels.

Discussion

Superhydrophobic (SH) surfaces have been around for over 20 years. SH surfaces to date have been used in several ways like anti-fog coating, anti-freeze surfaces, oil and water separation, anti-bacterial surfaces, medical applications, and drag reduction for maritime vessels.[M] (see figure 42) SH surfaces have two significant drawbacks. First, when they are submerged for long periods, they become wet and lose the SH capability. Second, SH surfaces wear down, losing the desired effect of the material.[H] These drawbacks do not limit the current use of SH surfaces but limit the effectiveness of this capability for long duration and cost-effective product viability in naval ship development.

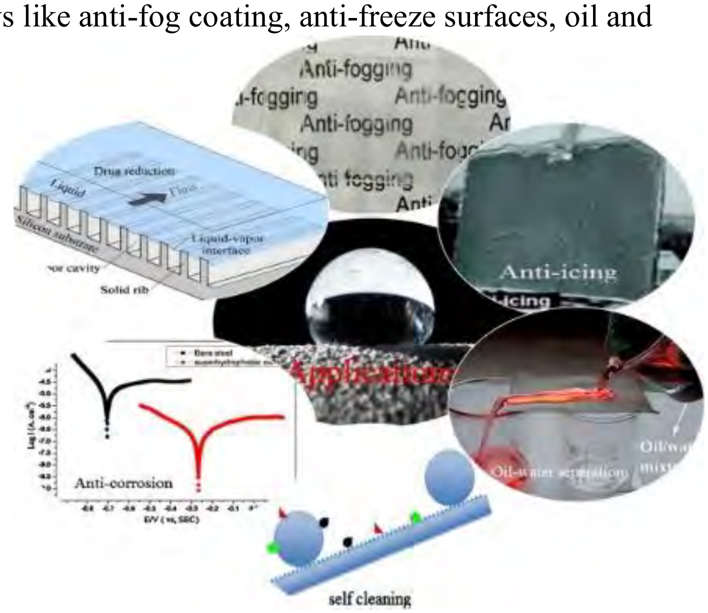

Figure 42: Examples of Superhydrophobic Uses. (Courtesy of Science Direct)

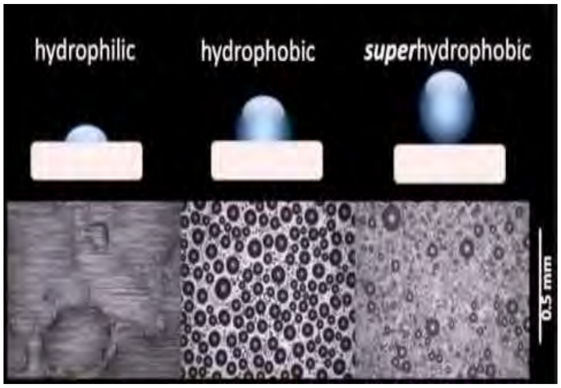

Figure 43: Levels of phobicity. (Courtesy of Konrad Rykaczewski)

The University of Rochester has developed a method to counter the drawbacks of SH surfaces. SH surfaces are based on nature. Inspired by how spiders and ants survive long periods under or on the water's surface by trapping air in an enclosed area, scientists developed techniques to mimic how these animals did this.[H] SH surfaces work by creating a surface where a water droplet beads up on the surface with a contact angle $\theta > 150°$.[H] These hydrophobic surfaces have a barrier-like property that causes them to repel water.

Figure 44: Unsinkable metal construct. (Courtesy of ACS Publications)

Using a femtosecond laser, the researchers at the University of Rochester created superhydrophobic property, using the laser for etching micro-and nano-scale patterns onto a structure's surface. They used femtosecond lasers, which emit pulses of light for an ultra-short period of time, to the tune of 10−15 seconds to create the patterns.[H] This step alone does not solve the drawbacks associated with SH surfaces. Next, the researchers, using two aluminum pieces, created a structure in which the treated surfaces on two parallel aluminum plates face inward, not outward, so they are enclosed and free from external wear and abrasion.[H] (see figure 44) The assembly demonstrated an unprecedented floating ability. During the research, the scientists were able to show that the design was able to float back to the surface even after being forced to submerge underwater for months.[H] This solved the first of the two major drawbacks of SH surfaces. Next, the scientist put numerous holes in the assembly, causing significant damage to the structure. (see figure 45)

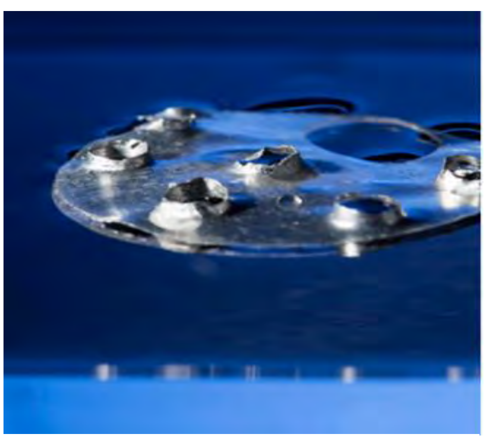

Figure 45: Damaged metal. (Courtesy of ACS Publications)

Even after this structural damage was inflicted, the assembly maintained its SH property because the surface maintained the trapped air. The damage did not wear off the etching because of the design, thus overcoming the second major drawback of SH surfaces.[H]

This new approach to SH surfaces can be used on any metal, but to be feasible for markets, the researchers noted that it will take faster lasers to create these patterns efficiently enough to make economic sense at scale.[M]

Figure 46: Visualization of Global Leaders in Shipbuilding. (Courtesy of Maritime Insight)

The Chinese have shown the capability, capacity, and willingness to modernize their shipbuilding industry to compete and dominate the world's naval arena.[M] China's naval modernization effort has been underway for more than 25 years. It has transformed China's navy into a modern and capable force.[M] As of 2019, China was one of the top three shipbuilding nations by gross ton globally.[M] (see figure 46) In a recent report conducted by RAND, China has approximately 1200 shipyards that produce a wide range of vessel sizes and types.[M] In comparison, the US has 124 shipyards that are classified as active shipbuilders. More than 200 shipyards were engaged in ship repairs or capable of building ships but were not actively involved in shipbuilding. This equates at best case, roughly 324 shipyards in the US.[M]

The Chinese have shown a steady, consistent pattern of technological modernization and capacity expansion since the early 1980s.[M] An example of this is China's rapid retiring of older single-mission warships in favor of larger multi-mission vessels equipped with advanced anti-ship, anti-air and anti-submarine systems, sensors and command-and-control networks.[M] Some of this modernization has resulted from technical cooperation between Chinese shipbuilding yards and foreign shipbuilders. These interactions provided Chinese shipbuilders with access to R&D techniques, production technologies, and management practices, which helped raise the design and production capabilities at various Chinese shipyards.[M] In their continued development of naval capability and a large sector of shipbuilding capacity, the Chinese likely have the will and ability to produce unsinkable metal at scale in five to ten years for both commercial and military use.

The Chinese still have hurdles to overcome to reach this point but likely will overcome them. RAND, in their study, points out, "… Despite the consistent improvements in design and production capabilities over the past 25 years, Chinese shipyards still suffer from three separate but related categories of problems: financial, technological, and managerial. There is poor cost control; production still uses outdated and inefficient equipment and technologies, and there is poor management of large shipbuilding projects." [M]

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were generally reliable and tended to corroborate one another. Limited study of Chinese shipbuilding capability and R&D abilities further reinforced the confidence level of this report. There was adequate time, but the student worked alone and did not use a structured method.

Microbiome Research Will Highly Likely Impact Enhancement of Soldier Health by the Year 2025

Executive Summary

Rapid advances in human microbiome research will highly likely impact human health enhancement by the year 2025. Recent findings linked intestinal bacteria with its effect on the Central Nervous System (CNS), and the impact on diseases such as Multiple Sclerosis, Alzheimer's, Parkinson's, anxiety, and depressive-like disorders. Despite regulatory hurdles in the probiotic/microbiome field, one venture capitalist firm predicts revenue will likely reach 10 billion by 2024.

Discussion

Microbiome research has been around for years, yet the understanding of how important the interaction of bacteria systems on and in the human body is increasing.[M] Research in 2020 identified how intestinal bacteria can affect the CNS by communicating in a bidirectional network with signaling pathways called the gut-brain axis.[H] (see figure 47) The understanding of the intestinal microbiome is likely to strengthen future disease prevention strategies, personalized healthcare regimens and novel therapeutic interventions.[M] The understanding of how the community of bacteria, fungi, mites and viruses which live on our skin can provide protection against disease and can promote or delay wound healing is also increasing.[H]

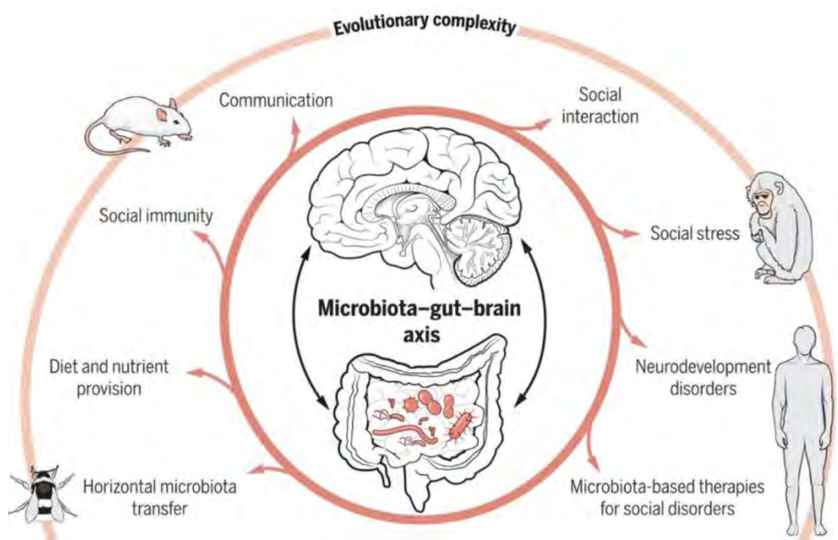

Figure 47: Microbiota-gut-brain axis. (Courtesy of Science Journal)

Figure 48: Microbiomes interact within the body throughout the day and night. (courtesy of Vital Nutrients)

The microbiome interacts with over 70% of the immune system, turning genes on and off, and the circadian rhythm.[H] (see figure 48) The identification of microbiomes which impact the body will likely provide a customized approach to health enhancement. Current research is already leading to possible commercial therapies.[H]

The Wyss Institute for Biologically Inspired Engineering at Harvard identified distinct bacterial microbiomes in elite athletes, which consistently occur in speed, strength and peak endurance performances.[H] The microbe, Veillonella, is likely responsible for enhanced endurance levels and lower inflammation rates among elite athletes by turning lactate into something anti-inflammatory.[H] The microbiome biotechnology company, Fitbiomics™ , conducted a beta test of its first probiotic last year, and expects to begin commercial production in May 2021, although this probiotic does not include the lactic acid metabolism microbiome.[H]

The study of microbiomes on the skin reveals a single square centimeter of skin can contain up to one billion microorganisms.[H] Research into understanding how skin microbiomes react when disease is present, gives insight into how to restore them to their natural state through manipulation of the microbiome.[H] Studies show microbiomes on the skin can fight pathogens, one in particular, inhibited the growth of MRSA.[H]

A patent published on 7 January 2021 (US20210000886) provides a solution to the shortcomings of probiotic preparations, by combining two factors, an intestinal microbiome analysis of the individual and the individual's medical history, after which a specific formulation of selected probiotic cultures was prepared to generate a resultant probiotic composition.[M] Researchers have found a difference in the guts of autistic and non-autistic children. Using Fecal Microbiota Transplants (FMT), the symptoms of autism can be reduced.[H]

The commercial success of microbiome therapies requires regulation of probiotics due to the uniqueness of each product, its impact on individuals and the vagueness of claims by manufacturers.[H] Another reason to regulate probiotics is the finding of how microbiomes interfere with some drugs and how other drugs are codependent with microbiomes.[H] Despite regulatory hurdles in the microbiome field, global venture capital firm, SOSV, predicts the race to translate microbiome research into commercial therapies is under way with revenue expected to begin in 2021 and reach 10 billion by 2024, while continuing to steadily climb in the decade beyond.[M]

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were reliable and tended to corroborate one another. There was adequate time, but the analyst worked alone and did not use a structured method. Furthermore, given the lengthy period of the estimate, this report is sensitive to change due to new information.

Carbon Nanotube Transistor Technology is Highly Likely to be Used in Military Radio and Communication Platforms by 2030

Executive Summary

Due to recent breakthroughs in production techniques and product purity, it is highly likely that carbon nanotube technology (CNT) will be used in the radio and communications industry by 2025 and in military radio and communication platforms by 2030. CNTs are 30 years old and have been, until recently, expensive, and difficult to produce for commercial use. In just the last two years, however, researchers at the University of Southern California, Carbonics, Inc., and MIT have developed processes that can produce CNTs at commercial scales and that can compete in price with silicon computer chips. While investment capital needed to build commercial manufacturing facilities and upscale production has traditionally been an issue for CNTs, these recent research developments are likely to dramatically reduce barriers to entry into this field and encourage entrepreneurs.

Discussion

Carbon nanotubes are nanometer diameter, cylindrical carbon tubes. They are single-wall carbon nanotubes (SWCNTs) less than 1 nanometer in diameter but can also be found in a multi-wall carbon nanotube (MWCNT) configuration. SWCNTs were first discovered in 1993 and came into the limelight in radio transmission in 2007.[H] In 2007, a research team from Lawrence Berkeley National Laboratory, University of California-Berkeley broadcasted a song across the FM spectrum using a single carbon nanotube as the radio.[H] This was a surprise discovery because the single nanotube was, effectively, all four components of a radio (antenna, tuner, amplifier and demodulator) at once.[H]

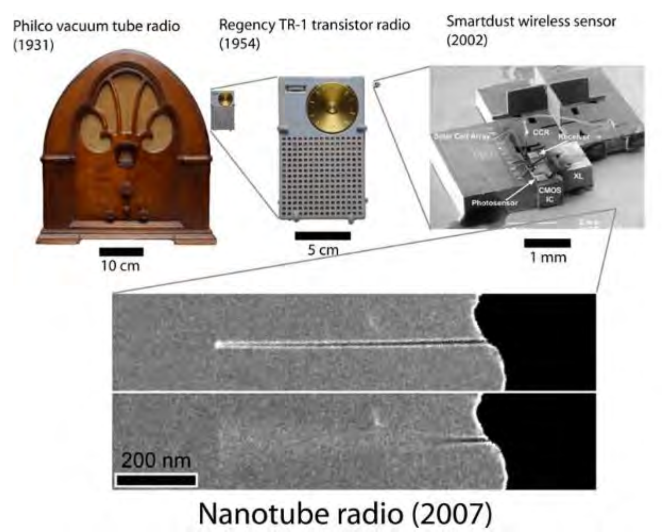

Figure 49: Decrease in radio size over the past century. (Courtesy Zettl Research Group, Lawrence Berkeley National Laboratory and University of California at Berkeley)

Since then, researchers speculated on the potentials for SWCNTs use as a high-frequency (HF) transistor technology.

Favorable characteristics of SWCNTs are ultra-high strength, low-weight material, possess highly conductive electrical and thermal properties, and the single most important characteristic for use in communication is a one-dimensional electron transport channel. It is this single dimension structure that will likely give CNTs the edge over multi-dimensional copper or silicon structures used in communications and transistors industries today. The benefit of one-dimension is summed up by Christopher Rutherglen, a researcher at Carbonics, "For example, as electrons are transported through any material, there is a tendency for them to scatter or collide along their path of travel, which ultimately reduces the speed of the overall device. In one-dimensional materials such as carbon nanotubes, electrons can travel much longer distances before scattering because there are fewer available states the electron can scatter into. Put simply: It cannot scatter up or down, right or left, because no such states exist in 1-D materials."[H]

The initial difficulty with using CNTs for technological or synthetic applications came from the CNT manufacturing process. The process to manufacture CNTs is very costly, slow, and difficult to produce high purity products. [H] Researchers at Rice University are pursuing processes to increase the growth rate of the CNT (see figure 50). Their research produced CNTs that are comparable to metals such as copper, but the cost of production is still too high, at least an order of magnitude higher.[H] The cost of production decreased over time but not by enough to make it commercially viable, and achieving high purity is still a challenge. There are three methods of CNT manufacturing recognized in the industry: chemical vapor deposition (CVD), arc discharge, and laser ablation.[H] Of these three methods, CVD produces the highest purity forms of CNTs, but still requires extensive processing after manufacture to remove impurities such catalysts, substrates, and amorphous structures.[H] A novel approach taken by scientists in China uses single-strand DNA to produce scalable biogenerated CNT transistors.[H] This approach is likely to prove to be more cost effective, but the research is still in its infancy. These manufacturing costs continue to keep the price of CNTs high. Despite the high cost in purifying CNTs, researchers continue to pursue projects to develop CNTs for use in communications and radio.

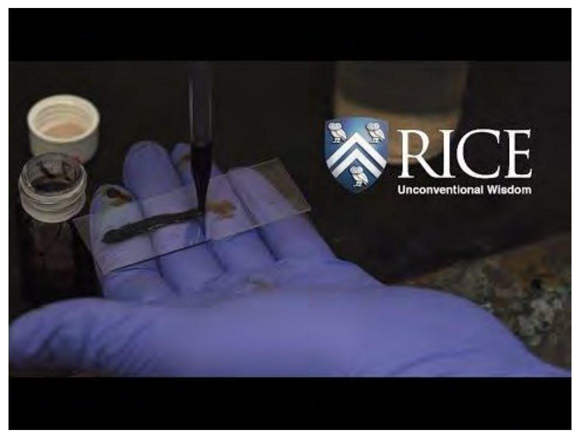

Figure 50 (video): Increase the growth rate of carbon nanotube fibers. (Courtesy of Rice University) To view click on the photo.

In 2019, Carbonics Inc., in partnership with the University of Southern California, had a breakthrough in CNT transistor technology.[H] There manufactured a CNT transistor capable of operating in radio frequency speeds at higher than 100 GHz. [H] This breakthrough put CNT transistors on a level to compete with current chip technology that predominantly uses silicon[H] or III-V technologies.[H] Like silicon technologies, CNTs are compatible to the workhorse of the electrical system, the conventional metal oxide semiconductor (CMOS). [H] It is highly likely that CNT transistors will increase the functioning of commercial communications systems, to include radar, radio, and wireless networks such as 5G, within the next five years. [H] The limiting factor is the investment capital needed to build commercial manufacturing facilities and upscale production. If investments in the commercial sector comes quickly enough, it is likely that the military sector will see widespread use of this technology in the next 10 years. [H]

Though these lab manufactured transistors are highly likely for use in the communications industry, there is not a process to produce them at commercial scale. In June 2020, researchers at MIT demonstrated the ability to manufacture a CNT transistor through a commercial facility using two new techniques for CNT deposition on the chip.[H] These new processes take CNT transistors closer to becoming a reality through commercial manufacturing, but it will take more time. The transistor developed by MIT researchers "had a gate length of 130 nm, which is equivalent to chips released in 2001. The new process also only achieved a CNT density of about 45 CNTs per micrometer, which is still significantly below the optimum of 200 predicted by previous research."[H] These transistors need to undergo long-term stability and reliability testing before they become a viable commercial option for 3-D transistors that outperform the current silicon chips.[H]

Another feature that makes CNTs, versus other similar technologies, desirable for investment dollars is their flexible nature. Due to the low diameter to high length ratio, CNTs are highly flexible, yet remain durable because of the strong carbon bonds.[H] This gives CNTs an advantage over solid silicon chips. There are other substances being studied to provide thin flexible transistors (TFTs) such as amorphous silicon and organic/oxide semiconductors, but the cost of manufacturing these other TFTs far exceeds the cost of CNT manufacturing, thus making them less desirable options.[H]

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were highly reliable and tended to corroborate one another. There was adequate time, but the analyst worked alone and did not use a structured method. There was adequate time to process the information. Given the lengthy period of the estimate, this report is sensitive to change due to new information.

Neural Lace Will Likely See Application Between 2030 and 2040

Executive Summary

It is likely that neural lace will be used in humans between 2030 and 2040. Rapid advances in BCI technology have led to a growth in research and money towards the field. Neural lace is an emerging technology in the field of BCI. It is likely to link human brains with computers without the need of a physical connection wired to the brain or body and allow for two-way communication. The limiting factors are the brain's ability to accept such implants, the longevity of electrode connections, and the number of neuron connections. An additional delay in the US is caused by the lack of timeliness of the FDA approval process.

Discussion

According to Big Data company CueLogic, "Neural lace is an ultra-thin mesh that can be implanted in the skull, forming a unit of electrodes for monitoring brain function.[M] One thing that differentiates neural lace from other existing BCI technologies is that it has now become possible to read and write the neural code thereby providing a two-way interface between a human brain and computer which was not feasible before."[M]

Neural lace inserted in the brain enters as a rolled-up electronic mesh injected through a hypodermic needle.[H] As the mesh leaves the needle it unravels, spanning the brain.[H] Over a period, injected lace is treated as a part of the brain and will move with it as it grows.[H]

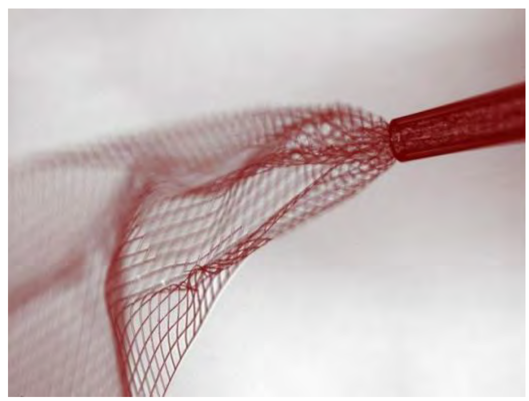

Figure 51: The rolled electronic mesh is injected through a glass needle into an aqueous solution. (Courtesy of Lieber Research Group, Harvard University)

In 2015 Dr. Charles Leiber and his team of scientists showed that mesh electronics with widths more than 30 times the needle diameter could be injected into the brain of a mouse and maintain a high yield of active electronic devices.[H] In the same study they also showed that mesh electronics injected into the brains of mice exhibit little chronic immunoreactivity, attractive interactions with neurons, and can reliably monitor brain activity.[H]

With the advent of Dr. Leiber's research and the announcement of the US National Institutes of Health Brain Research through Advancing Innovative Neurotechnologies initiative, in 2019, the past five years have seen the emergence of several other brain research initiatives and consortia, such as the US DARPA Neural Engineering System Design program, the Human Brain Project in Europe, the Brain Mapping by Integrated Neurotechnologies for Disease Studies project in Japan and the China Brain Project.[H] These research initiatives along with advances in nanoscience and unconventional electronics have converged to encourage the development of technologies that will enable high spatial integration (to record a large number of neurons simultaneously), long-term recording stability at the single-neuron level and multifunctional integration.[H]

Current invasive brain interface techniques experience problems with scaling of recorded single neurons. They fall short of Moore's law for three key reasons: the difficulty of increasing sampling volume without causing additional tissue damage; the difficulty of optimizing input/output interfaces in terms of accessibility to multiplexed, external recording instruments, bandwidth, and weight; and the difficulty of scaling electrode sizes to afford a higher density and sampling resolution.[H] Neural lace shows promise in that it has led to advances with respect to chronic tissue response and single unit recording stability.[H]

Since Elon Musk's purchase of Neuralink, he has put a focus on neural lace. Musk's neural lace would serve as a "digital layer above the cortex," he said.[H] Its components wouldn't necessarily require brain surgery for implantation; instead, the hardware could be injected into the jugular and travel to the brain through the bloodstream. [H] This less invasive approach would reduce the damage from direct penetration into the brain. But for now, neural lace is still in the early developmental stage and the Neuralink chip is its precursor. Neuralink has applied for FDA approval of the chip to be used as a BCI to assist medical patients with amputations or degenerative neurologic disorders.[M]

Report Attribute	Details
Market size value in 2020	USD 1390.49 million
Revenue forecast in 2027	USD 3.7 billion
Growth Rate	CAGR of 15.5% from 2020 to 2027
Base year for estimation	2019
Historical data	2016 - 2018
Forecast period	2020 - 2027

Figure 52: BCI market report forecast 2020-2027. (Courtesy of Grand View Research)

The Gartner hype cycle for emerging technology showed an increase in expectations from 2017 to 2018 for brain-computer interface technology.[H] It predicted that the technology was still more than 10 years out.[H] Grand View Research predicts a compound annual growth rate of 15.5% during the period of 2020 to 2027 (see figure 52).[H]

25 February 2019 the FDA published a draft of the Implanted Brain-Computer Interface (BCI) Devices for Patients with Paralysis or Amputation - Non-clinical Testing and Clinical Considerations.[H] This draft went out to institutes and industry for comments on the process.[H] Getting approval for brain interface devices is limited to devices that show a significant medical advantage over current devices for specific medical conditions.[H] The FDA has not accepted BCI devices for use outside of medical applications, therefore pushing goals of neural lace being used to enhance the human brain further into the future.[H] However, this does not apply to the research and application being conducted within other nations.

North America dominated the market for brain-computer interface in 2019, primarily due to high R&D investments and many clinical trials being conducted on brain devices in the region.[H] Asia Pacific expects to exhibit the highest growth rate over the forecast period.[H] Significant untapped opportunities, increasing healthcare expenditure, and growing awareness amongst patients expect to drive the demand for brain computer interface in this region.[H] Moreover, low-cost manufacturing sites and favorable taxation policies in this region attracted foreign players to invest in this lucrative market.[H]

According to Grand View Research, the military segment expects to witness lucrative growth over the forecast period of 2020-2027 owing to the increased use of brain-computer interface during war activities.[H] Development of mobile robots that can function as weapon-equipped drones in war zones and advanced communication systems such as DARPA "Silent Talk", which would enable soldiers and military personnel to give commands via telepathic communication, are anticipated to contribute to growth of this segment.[H]

Several challenges remain to public acceptance of neural lace. First, acute needle insertion damage during injection of mesh electronics leads to delays in FDA approval.[H] Second, there is a moral, ethical concern for neural lace use beyond the applications of medicine.

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were generally reliable and tended to corroborate one another. There was adequate time, but the analyst worked alone and did not use a structured method. Furthermore, given the lengthy time frame of the estimate, this report is sensitive to change due to new information.

Commercially Usable Fully Homomorphic Encryption Likely in Five Years

Executive Summary

Fully homomorphic encryption (FHE) analyzes or manipulates encrypted data without revealing the data to anyone except the person who has the key. Because of the increased focus on securing data related to cloud computing, and the growing demand for shared and third-party data, FHE will likely become commercially available within five years. Despite tremendous computing overhead and the need to develop a multikey version for business purposes FHE will quickly become the industry standard. This variant of FHE will likely provide an acceptable data protection level while balancing privacy with analytical capability.

Discussion

Commercial use of fully homomorphic encryption (FHE) will solve two major problems that exist today. The first is it will ensure that data remains secure and private in untrusted environments, like public clouds or with external parties. The data always stays encrypted, which minimizes the likelihood that sensitive information ever gets compromised. Second, it will eliminate tradeoffs between data usability and data privacy. FHE helps to solve these problems.

Homomorphic encryption can be broken down into three categories: partially homomorphic encryption, somewhat homomorphic encryption, and fully homomorphic encryption. The primary difference between these three types of homomorphic encryptions revolves around the types and frequency of mathematical operations performed on their ciphertext.[H] Partially homomorphic encryption (PHE) means that only one operation, either addition or multiplication, can be performed an unlimited

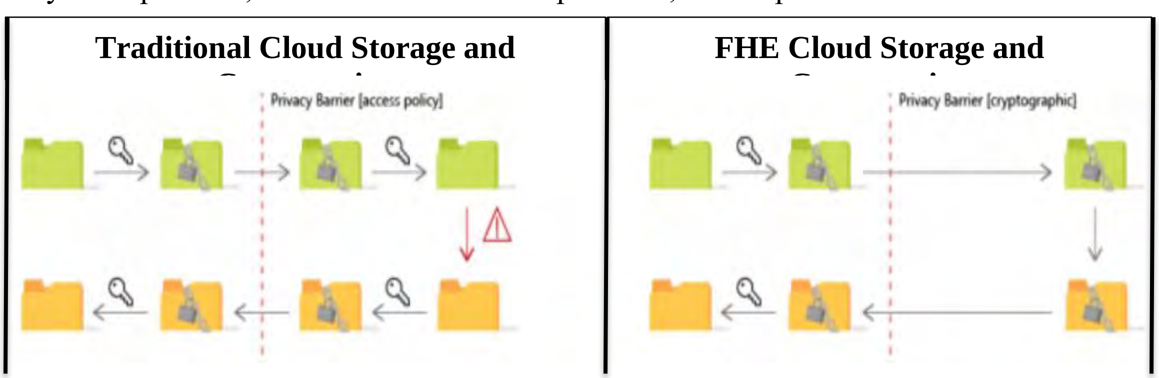

Figure 53: Visual representation on today's storage and computational method versus an FHE enabled environment. (Courtesy of Microsoft SEAL: Fast and Easy-to-Use Homomorphic Encryption Library)

number of times on the ciphertext.[H] A somewhat homomorphic encryption (SHE) scheme allows a limited number of calculations on the ciphertext and uses both addition and multiplication operations. [H] FHE allows for computations using both addition and multiplication an unlimited number of times while remaining ciphertext. FHE provides the encrypted solution to the owner without requiring access to a secret (decryption) key. Figure 53 visually shows how today's encryption works for calculation with potentially exposed data when data is unencrypted to solve and what FHE will likely provide in the next five years.

Fully homomorphic encryption was developed in 2009 by Dr. Craig Gentry, while a graduate student at Stanford University, using an algebraic system to allow others to perform various computations (or operations) on encrypted data.[H] For a homomorphic encryption scheme to work, the data is represented as integers while using addition and multiplication as the operational functions.[H] This means it allows the encrypted data to be manipulated and analyzed as though it is in plaintext format without being decrypted.[H] Dr. Gentry, in his original paper, describes it this way:

> …At a high-level, the essence of fully homomorphic encryption is simple: given ciphertexts that encrypt π1, . . . , πt , fully homomorphic encryption should allow anyone (not just the key-holder) to output a ciphertext that encrypts f(π1, . . . , πt) for any desired function f, as long as that function can be efficiently computed. No information about π1, . . . , πt or f(π1, . . . , πt), or any intermediate plaintext values, should leak; the inputs, output and intermediate values are always encrypted.[H]

Since Gentry's groundbreaking work, several improvements have been made on this math to speed up the computations.[H]

Modern encryption makes it impossible to process data without first decrypting it and decrypting the data could leave it vulnerable to hackers. The security provided by FHE is one of the main advantages that this process has. The security is based mathematically on the Ring-Learning with Errors (RLWE) problems.[M] To understand RLWE, a basic understanding of the base problem Learning with Errors (LWE) is helpful for the explanation. Oded Regev in 2005 proved in his paper titled *The Learning with Errors Problem* that "the LWE problem asks to recover a secret s ∈ Zn q given a sequence of 'approximate' random linear equations on s."[H] This base problem proved as hard to solve as several worst-case lattice problems.[H] A lattice problem is a class of optimization problems related to mathematical objects called lattices.[M] LWE is a quantum robust method of cryptography. RLWE is the learning with errors (LWE) method but adds polynomial rings over finite fields.[M] RLWE is secure against quantum computers as viewed today in the cryptological society.[M]

Two significant hurdles remain in the continued development of FHE. The first challenge is how to improve the math that runs the encryption. FHE uses vast and complex algorithms to maintain the security of the data. Currently, FHEs have a significant computational overhead. The overhead increases runtime substantially and makes homomorphic computation of complex functions impractical.[H] The other issue with FHE is it does not have support for multiple users. To explain the second drawback of FHE, here is a brief example. An FHE system, given a database with multiple users to access it, would need to create a separate database for every user, which is encrypted using the user's public key. This solution is impractical for most businesses and limits shared productivity across the organization.[M]

While these shortfalls require much more work to make FHE commercially effective, there is global interest in developing the technology. Today North America is the leading region in the research and development of FHE.[M] Companies like Microsoft and IBM and many startups are heavily investing in solving the shortfalls behind FME.[M] Governments and businesses, like DARPA who invested $14 million to FHEs, are allocating funding to develop this technology.[M] In the business world, financial institutes and the medical field show particular interest in developing this technology.[M]

Figure 54: What Is Homomorphic Encryption? And Why Is It So Transformative? (Courtesy of [forbes.com)](forbes.com)

Additionally, governments are interested in this technology for both military and civil uses. On the civil use side, this technology would likely support the better execution of elections.[M] On the military side, with homomorphic encryption, an agency could perform an encrypted search on another agency's encrypted data without revealing the subject of the search. Meanwhile, the agency with the data doesn't have to decrypt it and expose it to the agency performing the search.[M] An indicator of how soon this technology may come to market is to look at the market analysis. Indicators point to significant growth in the homomorphic encryption field, with numbers generally showing growth of around 8.5% compound annual growth rate.[H] Seeing the market analysis and the major tech companies that have invested heavily in the further development of FHE; it is likely that in the next five years, FHE’s problems will be solved or minimized and will be commercially available.

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were generally reliable and tended to corroborate one another. There was adequate time, but the analyst worked alone and did not use a structured method. Furthermore, given the estimate's limited time frame, this report is sensitive to change due to breakthroughs and new information.

Sophisticated Volumetric Display Technology Likely in the Next 8-12 Years; Military Use Between 2035-2040

Executive Summary

Recent discoveries (c. 2018) into Volumetric Display Technology[14] will make it likely that 3D technology will start to dominate the commercial space over the next eight to twelve years with military use between 2035-2040. Despite several optically related technological challenges associated with Volumetric Display tech, it is likely that this industry's commercial nature, particularly its use in the advertising market and ability to incite greater human compatibility with digital content, will drive the adoption cycle.

Discussion

The idea of volumetric displays has been around since 1914, and until 2004 there were only two types (*swept-volumetric displays and static-volumetric displays*)[15&16] competing for the best method to produce a three-dimensional image. (see figure 55)H

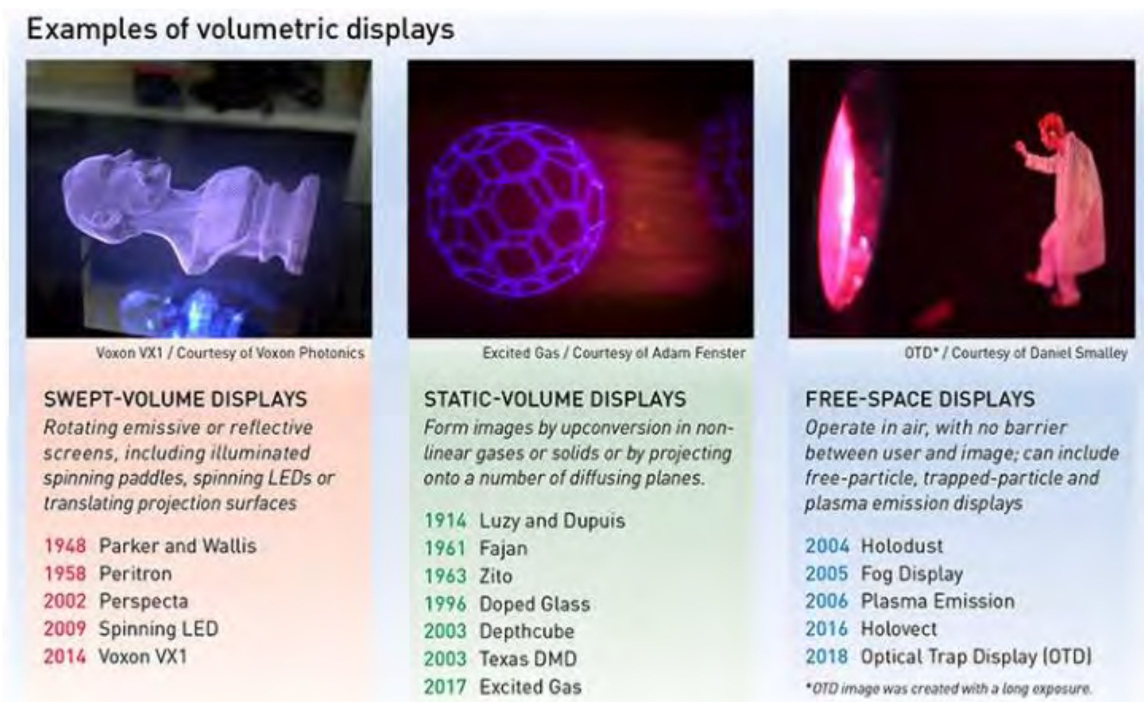

Figure 55: Picture depicting examples of Volumetric Displays and their dates of discovery. (Courtesy of Optics & Photonics News)

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[14] Volumetric Display Technology is the visual representation of objects in three dimensions, with an almost 360-degree spherical viewing angle in which the image changes as the viewer moves around.
[15] Swept-volumetric displays use the persistence of human vision to re-create volumetric images from rapidly projected 2D slices.H
[16] Static volume displays use no major moving parts to display images but instead rely on a 3D volume of active elements changing color or transparency to display a solid option.H

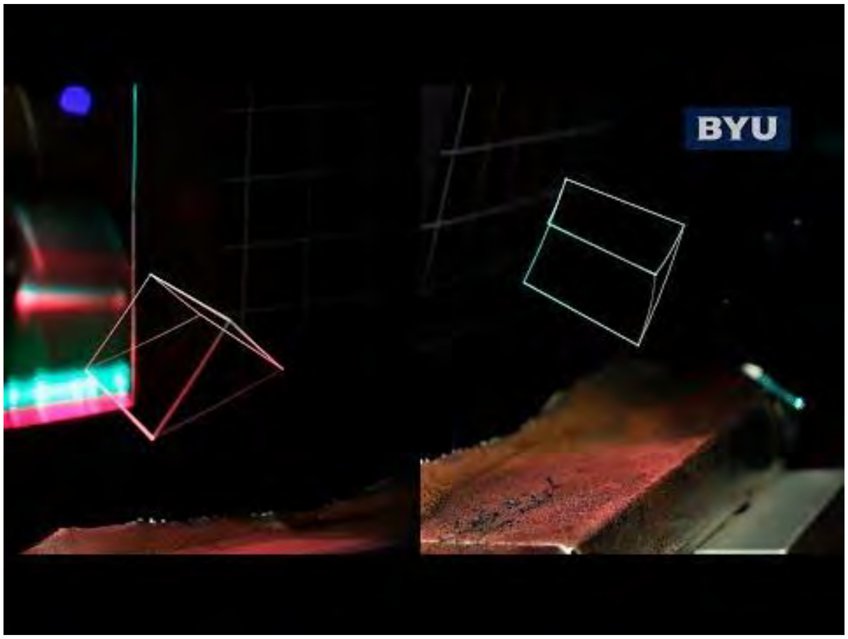

Figure 56: Dr. Daniel Smalley (Assistant Professor with the ElectroHolography Research Group within the Electrical and Computer Engineering Department at BYU) describes Photophoretic Trapping and Volumetric Display Technology. (Courtesy of Brigham Young University) To view click on the photo.

However, in 2018, Brigham Young University Professor Dr. Daniel Smalley led a small research team to a new technological discovery, dramatically advancing the third method. It allows light to print full-color graphics into thin air.H The team calls this technology an example of *free-space volumetric display*[17] using the Optical Trap Display (OTD) method based on photophoretic trapping.H Photophoretic trapping uses a laser beam to trap a particle and then move it around to create an image. A second set of lasers then projects visible light (red, green, and blue) onto the particle, illuminating it as it moves through space.M Humans cannot discern images at rates faster than ten per second, so if the particle moves fast enough, its trajectory appears as a solid line, like a sparkler in the dark.M (see figure 56)H

Volumetric Display technology is not a hologram[18], according to Dr. Frank Biocca, a professor at New Jersey Institute of Technology.H This technology creates visual representations of objects in three dimensions, with an almost 360-degree spherical viewing angle in which the image changes as the viewer moves around.H Dr. Curtis Broadbent, of the University of Rochester suggests, "you can have a circle of people stand around it, and each person would be able to see it from their own perspective. And that is not possible with a hologram."M

[17] Free-space volumetric displays, or displays that create luminous image points in space, are the technology that most closely resembles the three-dimensional displays of popular fiction.H

[18] A hologram is a real world photographic recording of an interference pattern which uses diffraction to reproduce a 3D light field, resulting in an image which still has the depth, parallax, and other properties of the original scene.

The medical industry is driving much of the early adoption. There is wide utilization of advanced display products for medical imaging applications such as MRI, X-ray, and CT scans.[M] There is also a growing need for volumetric displays in the defense industry to represent nearby land, air, and sea information.[M] In 2017, an Army Research Lab (ARL) report highlighted that 3D volumetric display technology is rapidly advancing, and in the not-too-distant future, interactive holography could be part of in-theater deceptive and camouflaging techniques.[H] Notably, the ARL report was published before the discovery of the photophoretic trap technology.

Photophoretic trap volumetric display technology will likely satisfy heavy commercial interest in the coming decade, particularly as the COVID-19 pandemic has fueled alternative modes of communication and interaction over distance. Lifelike telepresence,[19][M] virtual and in-person 3D medical processes,[M] gaming,[M] and advertising[H] will continue to promote this technology's speedy development. Additionally, there is a clear military advantage for those countries able to employ this technology. As alluded to in the ARL report,[H] military deception using fleets of fake ships, vehicles, or aircraft are likely to confound an adversary. The current global market value of volumetric display technology is $217.6 million and will likely grow to an estimated $2.389 billion by 2025.[H] The Garter technology forecasting firm suggests[H] the technology’s productivity plateau is likely to occur near 2030. With more research into the OTD method and of huge value to the defense industry, volumetric displays are likely to be very disruptive.

Photophoretic trap volumetric display technology is likely to face several technological challenges. These include trapping, scanning, scaling, robustness, safety, and occlusion.[H] Despite these challenges, they are clearly defined by researchers with accompanying potential solutions drafted for future work.[H] Similarly, the eventual projection of a human-sized display (as in Telepresence) requires many pixels (Terabits per second), and 5G technology's peak rate is only 20 Gigabits per second.[H] The 6G internet speeds will likely provide the necessary bandwidth for the technology's use.[H] According to a Samsung white paper, the International Telecommunication Union will begin work to "define a 6G vision" in 2021. The standard will likely be completed around 2028, commercializing the first 6G products around that time. The widespread deployment of 6G will happen around 2030,[H] offering two additional years for commercial proliferation. Military use will follow two to three years later as scaling up to platform-sized displays will require a more robust volumetric display infrastructure.[H]

[19] Telepresence refers to a set of technologies that allow a person to feel as if they were present, to give the appearance of being present, or to have an effect at a place other than their actual location.

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were reliable and tended to corroborate one another. There was adequate time to understand the information, but the analyst worked alone and did not use a structured method. The report is sensitive to change due to recent breakthroughs and new information.

4D Printing Highly Likely to Reach Commercial and Military Application by 2030

Executive Summary

4D printing, which allows traditional 3D printed products to alter their shape when certain external stimuli are applied, is highly likely to reach commercial and military application by 2030. 4D printing research is being driven by both high-profile programs in both academic institutions and business. Due to the nature of 4D printed materials being able to adapt to changes in the environment, it is highly likely to have impacts on the aerospace, medical, and construction industries. Further research is needed to determine the long-term integrity of 4D printed products and decrease cost in materials and processes.

Discussion

4D printing is essentially the same as 3D printing with the added element of the fourth dimension, time. The products for 4D printing are printed on a 3D printer. The difference is that the 4D printed products have two elements instead of one used in 3D printing: the rigid layered 3D structure (this is the product of 3D printing) and a geometrically coded flexible 3D structure.[H] This flexible element changes shape over time, as a stimulus is applied. This stimulus may be water, temperature, pressure, magnetic, or chemical in nature.

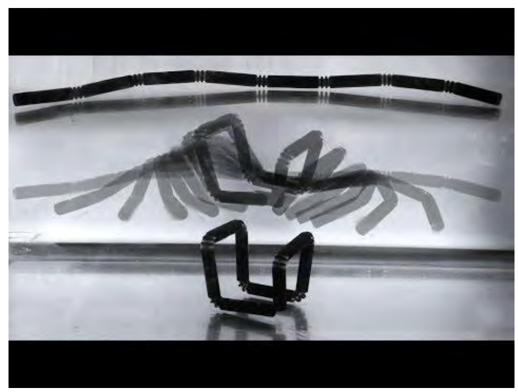

Figure 57 (video): What is 4D printing? (Courtesy of the B1M). To view click on the photo.

The two most commonly used substances for the flexible material are hydrogels or shape memory polymers. [H] Hydrogels are hydrophilic polymer chains induced to alter shape by changes in temperature or water content in the external environment.[H] Additional materials reserched for use as "smart" print materials are shape memory alloys and ceramics. [H] Figure 58 shows four 4D printed ceramics in their reconfigured formation. These ceramics were initially flat sheets, when exposed to the stimulus, they transformed into the shapes shown.[H]

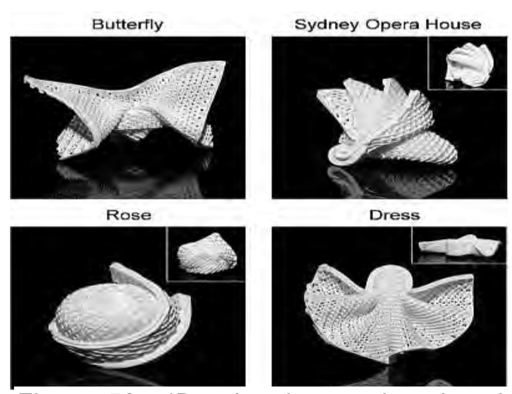

Figure 58: 4D printed ceramic origami. (Courtesy of City University of Hong Kong)

Research in 4D printing occurs largely in academic labs, but research also occurs in the private sector. MIT's Self Assembly Lab researches 4D printing. In the Self Assembly Lab, researchers pursue 4D printing using a variety of materials and techniques. Some of their successes in 4D printing are self assembling furniture, medical implant devices, and sports shoes.H Researchers at Harvard University worked on biologically inspired engineering using hydrogels to create medical implants. They produced 4D structures that create curvature unlike previous more linear models.H Researchers at the University of Wollongong in Australia created a functioning 4D printed water valve.H Research in the private sector is conducted by companies such as Autodesk, Hewlett Packard, Stratasys, BMW, Airbus, and Briggs Automotive Company.H

4D printing has application possibilities across most industries from medical devices and self-folding proteins to more efficient aircraft wings to sports shoes to computer processor parts to construction materials. With these materials being so versatile, there are many possible uses within the military. Military applications include flexible, self-healing body armor, self-healing vehicles, soft robotics, and self-emplacing bridges and structures. H

The 2018 Gartner Hype Cycle predicts the technology is more than 10 years out (see figure 59).H Forecasters predict aerospace and military industries to be the leading investors in 4D printing by 2025.H Though the US leads the research efforts, Grand View Research predicts Asia will be on par with the US in 4D print research by 2025. H

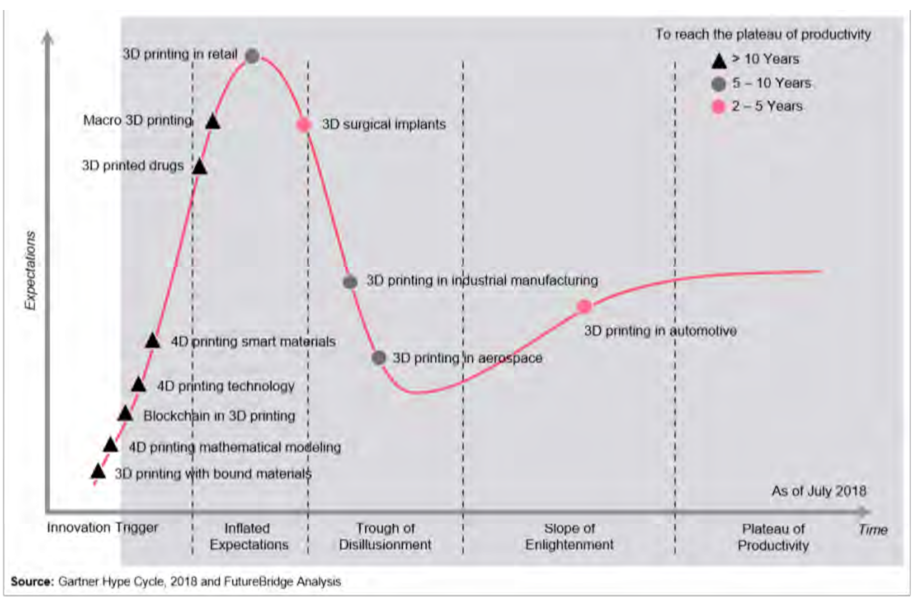

Figure 59: 3D and 4D printing on the Gartner Hype Cycle, 2018. (Courtesy of Gartner and Future Bridge)

4D printing faces several challenges beyond cost of print and "smart" materials. Before it can make its debut at the commercial scale, researchers have to address the issue of internal supports for larger structures.H This is a crucial element in construction and durability for some industries to show interest in 4D printing. This requires demonstrating that the structure has the necessary support to exist in its desired configuration over time. Long-term testing needs to ensure that a 4D printed structure will not resume its original form or some other weaker form if the external stimuli change. [H] To be used in industry, the parts developed need to meet standards and regulatory requirements and the medical applications require FDA approval and human subject testing. All of this takes time and investments. It is predicted that 4D printing growth will go from $62.02 million in 2020 to $488.02 million by 2026, at a combined annual growth rate of 41.96% over the forecast period (2021 - 2026), but more investment dollars are needed to make this a successful process for commercialization.[H]

Analytic Confidence

The analytic confidence for this estimate is *high*. Sources were highly reliable and very closely aligned with one another's analysis, notably as the research spanned the last decade. The analyst worked alone and did not use a structured method. However, the analyst did confer with the team regarding 4D printing rating as a surprise technology. There was adequate time to process the information. It is not likely that new information will change this estimate.

Widespread Use of “Electric Wood” in Technology Likely Within 10 Years, Military Use by 2030

Executive Summary

It is likely the use of “electric wood,” or wood products that conduct electricity or otherwise mimic other products traditionally found in electronics, will be widespread within 10 years and include military use by 2030, despite manufacturing process challenges. Research into the use of wood products in technology continues to evolve, increasing the availability of biodegradable circuits, conductors and smart materials which can be used in drones, robotics, and communication devices.

Discussion

In 2020, Bengston et al. published a paper on the technological innovations regarding wood products and the “coming age of wood”.[H] Some of the innovations include wood-based nanomaterials, biodegradable electronics, 3D printing cellulose from wood pulp, and transparent wood as a substitute for glass.[H] Another innovation is the production of electricity from wood products. In Switzerland, an experiment demonstrated the feasibility of functionalizing the production of electricity from wood products, which could generate voltage to run low-power electronics.[H] The experiment involved creating a cellulose structure from wood which produced an electric voltage when squeezed.[H] (see figure 60) The University of Wisconsin-Madison is currently testing a power generating wood flooring.[H]

Figure 60: Piezoelectric Nanogenerator: created from a wood cellulose structure which when squeezed, produces an electric voltage. (Courtesy of PHYS.ORG.)

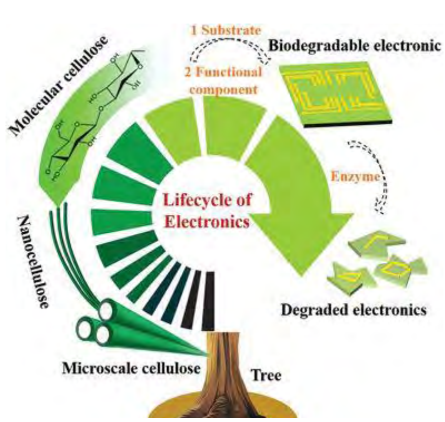

Figure 61: Lifecycle of Electric Wood. (Courtesy of X-MOL.COM)

Breaking wood down to the nanoscale creates wood-based nanomaterials.[H] (see figure 61) In 2020, a New Zealand based team created a wood based flexible circuit with strong mechanical properties, stronger than most engineering materials, and could be used in sensors, smart packaging and wearable devices.[H] Chinese backed researchers recognized wood cellulose could be used as a versatile polymer in biodegradable electronics as a functional component such as advanced light management layer, high capacitance conductor, or as a smart material such as a humidity sensor, adaptable adhesive or piezoelectric component.H A research team from the University of Wisconsin-Madison constructed a flexible, functional microwave amplifier circuit on wood fiber cellulose paper.H (see figure 62) Due to the circuit construction from wood fiber, it decomposes or burns easily, leaving behind no trace.H

Figure 62: Microwave circuit made of wood fiber cellulose. (Courtesy of EENEWSEUROPE.COM)

Biodegradable and renewable in nature, Cellulose Nanocrystals (CNC) are derived from cellulose fibers.H CNCs provide low cost, eco-friendly, sustainable materials which can be used for various applications such as electronics/sensors, biomedical and energy.H CelluForce, is the world leader in the commercial production of CNC, operating the world's largest plant.H CelluForce teams with other companies, giving them access to their largescale R&D network, while they control almost 20% of CNC Intellectual property/patents.H Schlumberger Technology Investments, a venture capitalist investment firm, invested in CelluForce.H

The expectation is 3D printing with cellulose from wood pulp will be cheaper, stronger and more environmentally friendly than working with plastics and other petroleum-based polymers.M Despite the manufacturing challenge of 3D printing with cellulose due to its breaking down during the heating process, the addition of additives helps negate the issue, though it decreases the cost-savings realized using cellulose.H Per the nano.gov website, "National Nanotechnology Initiative member agencies are working with the private sector to build an industry around America's forests by suppling plant-derived nanomaterials for everything from biodegradable electronics to high-strength packaging."H

Figure 63: Transparent wood possible use as electronic screen. (Courtesy of MSN.COM)

The University of Maryland and University of Colorado teamed to create a transparent wood, which can withstand stronger impacts and will bend or splinter when damaged.H This transparent wood can be used as a screen in electronics such as a cell phone, it is more resilient than regular screens and cheaper to produce.M (see figure 63) Swedish researchers created a semi-transparent wood which can be massed produced in larger sheets which can be used in solar cells.H

The application of a flexible circuit will likely impact an array of items such as wearable devices, drones and communication networks.[H] Possible Department of Defense use of biodegradable electronics with incorporated wood cellulose products, include drones and robotics with planned end of life timelines.[M] Another utility includes deploying electronics with heat-triggered self-destructing capability to increase the devices security.[H]

Analytic Confidence

The analytic confidence for this estimate is *high*. Sources were generally reliable and tended to corroborate one another. There was adequate time, but the analyst worked alone and did not use a structured method. Furthermore, given the lengthy time frame of the estimate, this report is sensitive to change due to new information.

Scalable 5-Dimensional Data Storage on “Glass” Production Likely Within 14 Years, Available Commercially Between 2040–2045

Executive Summary

Scalable data storage on “glass”, or 5 Dimensional (5D) optical data storage, is likely to enter production for government, military, and large-scale corporate use by 2035 and enter the commercial consumer market between 2040 and 2045. The nanostructure glass is used to store large amounts of data in a small area for an extremely long period. Companies heavily vested in traditional data storage mediums will likely ignore the movement due to the large investment in the required technology and the need for two different machines to read and write data. It is likely the 5D technology, when commercially viable, will drive new methods for storage and handling large data sets.

Discussion

5D technology was initially developed in 2013 at Southampton University in the United Kingdom.[M] It was not a vast improvement over other techniques since the process could only store a few hundred kilobytes of data.[M] Since the initial development and testing, the process advanced and the medium can currently store 360 terabytes of data on 5D nanostructure glass.[M]

Figure 64: Picture showing multi-layer 5D image and data on crystal medium. (Courtesy of *5D Memory Crystal)*

Data storage and access are becoming critical in the age of big data. Traditional mediums such as tape and hard drives need to transfer the data every few years to a new medium for long term storage, and newer methods such as solid-state flash and hard drives have a lifespan of around ten years at the most.[M] Cloud storage, one of the primary storage infrastructures used for data backup, still require information to be stored on a medium physically located in a facility and accessed remotely from a local computer, phone, or other device.[H] Additionally, long term data storage in a cloud infrastructure drives costs by needing to transfer data onto newer media on an incremental basis to retain the information.[H] 5D data storage will provide an option for a long-term solution to large capacity storage. 5D utilizes nanostructure glass and a femtosecond laser, the same laser used for LASIK eye surgery, to store approximately 360 terabytes of data, which can be retained for billions of years.[M]

The process of 5D storage does not actually write in 5 dimensions. The process writes data in "5 dimensions of glass", by orienting the glass and using the current storage dimensions and increasing the quantity of data stored on a given medium.[H] The data is read by using an optical microscope capable of decoding the "polarized light reflected by the three-bit spots used".[H]

Russia is pursuing a 5D storage project at the Advanced Research Foundation and is working with advanced quartz to develop a long-term storage solution.[M] Russia believes they can develop the technology to match the prices of current day hard drives, but they will not need to be replaced incrementally to retain data.[L] A team of scientists from France and South Korea are jointly researching the technology under funding from the French National Research Agency and the Korean Ministry of Science and Technology, ICT and Future Planning.[M] Researchers from the Sri Krishna Arts and Science College in India published a paper in an international technical journal highlighting future trends in data storage. The methodology and background information were presented but no significant research or funding was identified in the publication.[M]

The military and security applications of a large-scale 5D storage system will provide a large advantage over traditional electronically stored media. Government agencies and military organizations spanning large geographic areas will leverage large amounts of current and historical data without issue.[M] Big data yields multiple storage and processing obstacles for governments and 5D provides opportunities to redefine how it is stored and accessed.[L]

5D data storage will face multiple challenges limiting its entrance into large-scale production and a scalable marketplace. The technology of writing to the glass and crystal medium is still in its infancy and not matured to the point of being cost-effective.[H] Additionally, the technology is not advanced to the point the crystal can be used repeatedly, or in a "read and write" format, driving limitations for uses other than mass access and archival.[H] In addition, the control systems and laser used to record data onto the storage medium are larger platforms without the form factor

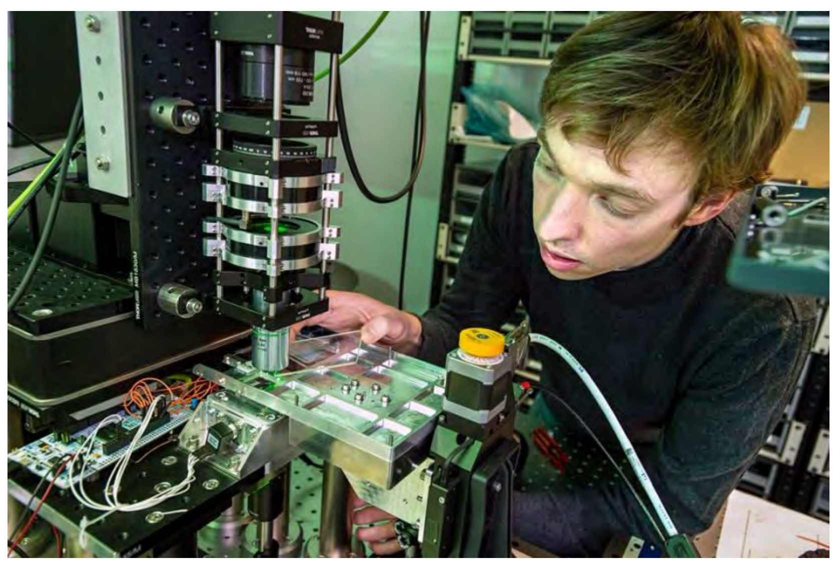

Figure 65: Scientist loading glass into system used to retrieve and store data on glass. (Courtesy of Microsoft)

required to integrate the technology into organizations for daily use.[H] Current technology does not allow the same machine to both read and write data to the storage medium, requiring two separate machines to conduct the required tasks.[H]

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were generally credible and did not demonstrate any bias. The analyst worked alone and did not use a structured method. The topic matter and research were not complex, and there were no time constraints on the assessment. Based on the speed and priority of the development, there is likely to be new information available in the foreseeable future for an update.

Additional Findings

Biodegradable Sensors Almost Certain Within 10 Years, Field Deployable Between 2032–2037

Executive Summary

Research advancement in biodegradable sensors will almost certainly enable medical use for monitoring physiological parameters after surgery within the next 10 years. The military's use of biodegradable sensors within the medical community will almost certainly follow civilian medical advancement, however the military application of biodegradable sensors on the battlefield as a process to improve Soldier performance requires further exploration to become deployable between 2032 and 2037.

Discussion

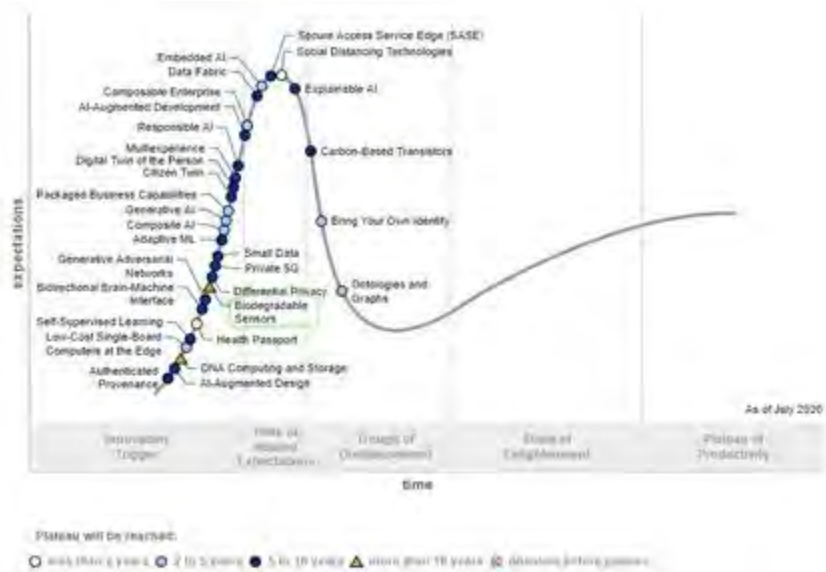

Figure 66: Hype Cycle for Emerging Technologies, 2020. (Courtesy of Gartner)

As technology advances, the use of sensors in everyday life increases. Most are durable electronics, for example, a watch that monitors your heart rate, sleep patterns, and blood oxygen levels. Advancement in sensor research includes multiple clinical research teams working to develop biodegradable sensors which can be placed within the body.[H] In August 2020, respected tech-forecasting firm Gartner identified Biodegradable Sensors in its 2020 Hype Cycle for Emerging Technologies, as one of five emerging trends for the next 10 years.[H] (see figure 66)

Two different Chinese research groups published papers in 2020 describing research into biodegradable sensors. One group researched body-integrated, biodegradable sensors for health monitoring and in situ treatment.[H] (see figure 67) The researchers, Zhang et al, discuss a key challenge; how the material must be physically durable and biocompatible.[H] Their answer: silk proteins which can be processed into multiple material formats, doped with graphene, and carbonized which allows for conductive suspensions and electrical conductivity.[H] The second group's research involved creating a biocompatible and biodegradable polysaccharide-based flexible humidity sensor which could monitor human respiration.H

Engineers at the University of Connecticut developed an implantable pressure sensor encased in an FDA approved medical grade polymer which degrades inside living tissue.H The FDA continues to approve biodegradable polymers as scientist continue to research and test different types.H A research team from Stanford University developed an implantable, biodegradable sensor for medical monitoring which measures strain and pressure, as part of a larger project researching biodegradable electronics.H

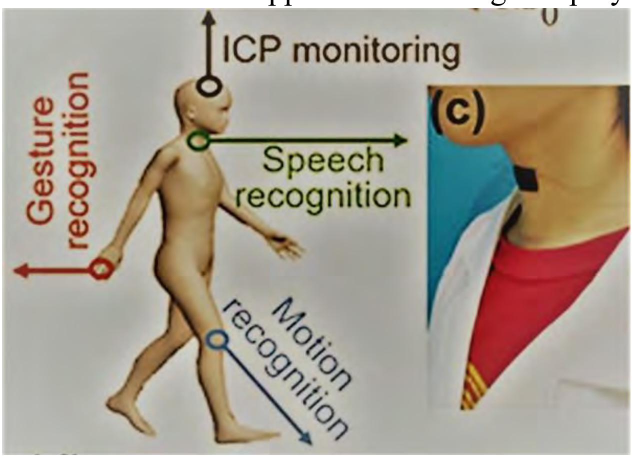

Figure 67: Sensors placed within the body provide Intracranial pressure (ICP) monitoring, and speech, motion, and gesture recognition. (Courtesy of Wiley)

In the future, a Soldier might receive multiple implants which monitor for physiological parameters, metabolites, and biological/chemical agents. Karl E. Friedl states in his 2018 paper on Soldier physiological monitoring, "Military operational applications include: (1) technological enhancement of performance by providing individual status information to optimize self-regulation, workload distribution, and enhanced team sensing/situational awareness; (2) detection of impending soldier failure from stress load (physical, psychological, and environmental); (3) earliest possible detection of threat agent exposure that includes the "human sensor"; (4) casualty detection, triage, and early clinical management; (5) optimization of individual health and fitness readiness habits; and (6) long term health risk-associated exposure monitoring and dosimetry."H Though initially designed for medical use, the development of body-integrated, biodegradable sensors for use in monitoring a Soldier on the battlefield would improve Soldier performance. FDA approval for medical devices take an average of three to seven years to bring the device to market.H

Analytic Confidence

The analytic confidence for this estimate is *high*. Sources were generally reliable and tended to corroborate one another. There was adequate time, but the analyst worked alone and did not use a structured method. Furthermore, given the lengthy time frame of the estimate, this report is sensitive to change due to new information.

Neuromorphic Computing Likely Within 5 Years, Field Deployable Between 2030–2040

Executive Summary

Neuromorphic computing, and the ability to emulate the neural network found in human brains, is likely within five years and field deployable in nine to nineteen years in large part due to the aggressive pursuit of artificial intelligence (AI) technology and the global pursuit of expanding AI applications across multiple defense and commercial sectors. The successful development of a neuromorphic system could create systems capable of learning, reasoning, remembering, and help humans make more informed and efficient decisions in extremely short timeframes. There are challenges with neuromorphic computing as well. The ethics of computer-based decision making, and the technical obstacles associated with neuromorphic systems have yet to be resolved.

Discussion

The global effort to integrate AI into daily processes and tasks drives innovation and furthers technology development. Neuromorphic computing uses neural networks to execute the cognitive process or closely emulate the brain's neural structure.[M] The international community is taking full advantage of AI's technological leaps made over the past few years. More importantly, key US competitors are furthering their research, optimizing neuromorphic computing techniques, and making significant headway. The aggressive pursuit of neuromorphic computing by peer and near-peer competitors is indicative of the importance the countries place on the technology and their intent for integrating it into key areas of the government and commercial enterprises.

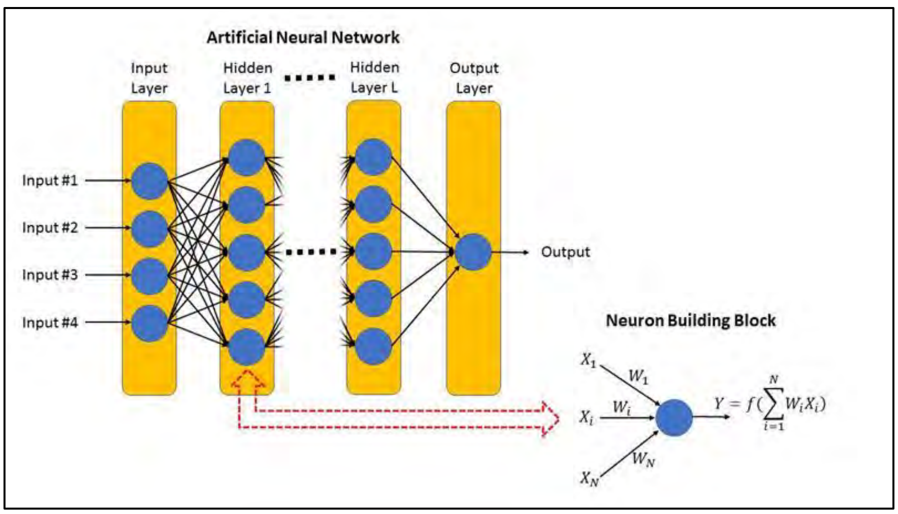

Figure 68: Artificial Neural Network Schematic. (Courtesy of Singularity 2030)

The military applications for a neuromorphic computer system are extensive and will likely change the dynamic and nature of future warfare. China is remodeling their strategy from fighting an "informationalized" war to an "intelligentised" war and is integrating the technology into AI-driven military training and Command and Control.[M] Tsinghua University is charged with establishing the High-End Laboratory for Military Intelligence (HELMI) and driving what China refers to as "AI superpower strategy", indicating the level of emphasis they place on the integration of the technology into the military infrastructure.[M] Based on the research emphasis and funding dedicated to neuromorphic and "brain" computing, China is committed to developing the technology and are likely capable of fielding a neuromorphic military platform in advance of the forecasted timeframe.[M] The Russians share an elevated level of interest in neuromorphic computing for military applications. While Russia lags the US and China on overall AI research, they are increasing their emphasis on the technology, including neuromorphic computing applications, and researching solutions for the concept of replacing soldiers on the battlefield and pilots in the cockpit[M] with AI

Figure 69: Chinese Scientists with the Darwin Mouse. (Courtesy of Abacus Tech)

China placed neuromorphic computing as a priority in its 13th Five-Year Plan and set the goal of reaching "world-leading levels by 2025." [M] China backed up its goal by establishing multiple research labs and sponsoring the "China Brain Initiative" and "Beijing Brain Initiative" with funding levels exceeding $50 million annually.[M] China made a significant achievement when they developed the "Darwin Mouse" with the same number of neurons as a living mouse.[M] The "Darwin Mouse" was able to control multiple small-scale robots as a proof of concept for neuromorphic computing.[M] Additional programs for "national-level development of brain-inspired intelligence" are being pursued and funded at levels exceeding $2.8 billion annually.[M]

Russia placed AI and neuromorphic computing as a priority, but funding and research may not support their desired end state, despite this, Russia is aggressively pursuing their research goals. Russia released their AI strategy in October 2019, and specifically identified neuromorphic computing, and is focused on the "development of prospective system architectures (including neuromorphic computing systems)." [M] Additionally, Russia is making breakthroughs in developing hardware needed to field a neuromorphic capable system.[M] Russia created a new defense organization, the Foundation for Advanced Studies to support the development and modernization efforts and military goals.[M] Their overall defense modernization agenda is aggressive and is focused on robotizing 30% of its military equipment by 2025.[M] Their desire to drive AI and neuromorphic computing throughout the country is not supported by their budget and level of research. Russia's research spending is expected to drop between 2020 and 2022, and Russian academics are not producing the number of academic papers to keep pace with the US and China.[M] Despite Russia's desire to maintain pace and drive the development of neuromorphic computing, they may not be financially situated or have the expertise to keep pace with other countries leading the technological development.

Neuromorphic computing, and AI in general, share some common challenges. The human brain runs on approximately 20 watts, while computers executing complex algorithms require much more energy.[H] While neuromorphic systems use significantly less energy than normal computers, they still require more than the human brain and need further development and refinement to evolve into a desirable form factor.[M] Evolving from a traditional computer infrastructure to an AI-centric network will force companies, governments, and in turn, militaries to shift to neuromorphic computing model to keep pace with peer and near-peer adversaries.[M]

Deploying an operational and fully integrated neuromorphic computing system presents problems and issues yet to be resolved. The back end of the system, on-chip memory, and processors are some of the hurdles to producing a scalable and efficient neuromorphic system with complex learning algorithms as another large hurdle.[M] The ethical issues surrounding AI and neuromorphic computing are also challenges for the future. They will require governments to implement safeguards and ensure checks and balances to drive consistent and ethical decision-making procedures.[M] The challenges do not outweigh the benefits, and at the current rate of development, countries leading the development of AI systems and process may overcome the challenges in the foreseeable future. Ultimately, if the development remains consistent and stable, neuromorphic computers may have more in common with how humans think than computers.[M] Despite the current challenges, independent and state sponsored research is not likely to overcome most technical or ethical issues to field neuromorphic systems in a timely manner.

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were generally credible and did not demonstrate any bias. The analyst worked alone and did not use a structured method. The topic matter and research were not complex and there were no time constraints on the assessment. Based on the speed and priority of the development, there is likely to be new information available in the foreseeable future for an update.

China Likely to Use Quantum Radars Within 10 Years

Executive Summary

In 2016, a Chinese firm, the Intelligent Perception Technology Laboratory of the 14th Institute in the Chinese Electronics Technology Group Corporation (CETC) and, a defense and electronics firm, developed and tested a quantum radar system that could defeat the stealth technology of modern military craft. Since that time China has invested billions of dollars into research in the field of quantum science to improve on this early development. There are scientists in the field of quantum radar/quantum illumination that believe that a quantum radar is unlikely to go beyond the laboratory due to quantum decoherence and other challenges. Based on the findings in this report, quantum radars are likely to be in military production within the next 10 years.

Discussion

Quantum radar technology is based on the principles of quantum illumination and quantum entanglement. A quantum radar uses a source of entangled photons that are strongly correlated and have the same inseparable identity and experiences and work as one quantum system, even when separated. To detect an object at distance, a beam of photons is split, with one half transmitted and the other retained at the base station for comparison with the reflections. Quantum radars provide two key benefits over current radar systems. First, they will require less high-energy radio signals to have the same range as current radars.[H] The reduction in high-energy radio signals makes quantum radars nearly undetectable. Second, a quantum radar will provide an ultra-high-definition radar picture.[H] The result of this new technology is instead of an indistinguishable blob on a radar scope, the system will have the ability to make out fine details of an aircraft. Building better, more sensitive, and harder-to-detect radar systems remains a key focus for national defense strategies around the world today. Several countries, including the US, Canada, China, the EU, and Russia, are interested in developing a quantum radar.[M]

Quantum radars work by using quantum entanglement as a method of object detection.[H] Quantum entanglement is a physical phenomenon whereby two particles remain interconnected, sharing physical traits regardless of how far apart they are from one another.[H] A conventional radar searches for objects by detecting pulses of microwaves reflected from them; quantum radars utilize pulses of microwaves linked by a quantum connection. The quantum radar system entangles two groups of photons, which are called the signal and idler photons.[H] The signal photons are sent out towards the object of interest, while the idler photons are measured in relative isolation, free from interference and noise. When the signal photons are reflected, true entanglement between the signal and idler photons is lost. (see figure 70) However, a small amount of correlation survives, creating a signature or pattern that describes the existence or the absence of the target object—irrespective of the noise within the environment.[H]

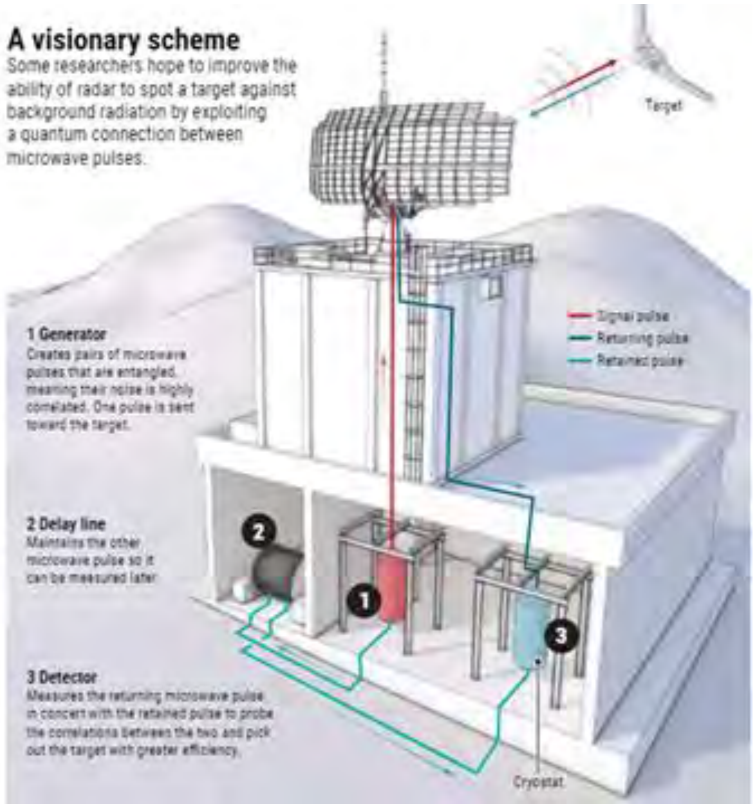

Figure 70: How a Quantum Radar works image from Adrian Cho. (Courtesy of Science Mag)

One of the recent successes in the quantum radars' field was done by a team from the Institute of Science and Technology Austria. [H] In a laboratory setting, this team was able to build a quantum radar capable of spotting objects at lower temperatures and with less background noise than existing radars.[H] Even with the successes that scientists are having with quantum radars' development, there are likely challenges to turning this from a laboratory success to a field-ready device.[M] The main challenge that must be overcome is quantum decoherence.[M] Wikipedia defines quantum decoherence as, "quantum decoherence is the loss of quantum coherence. In quantum mechanics, particles such as electrons are described by a wave function, a mathematical representation of the quantum state of a system; a probabilistic interpretation of the wave function is used to explain various quantum effects. If there exists a definite phase relation between different states, the system is said to be coherent."[20] A definite phase relationship is necessary to perform

[20] *Wikipedia, The Free Encyclopedia,* s.v. "Quantum decoherence," last modified February 03, 2021, https://en.wikipedia.org/wiki/Quantum_decoherence

quantum computing on quantum information encoded in quantum states like quantum radars.

Deploying quantum radars is highly likely to provide a significant tactical advantage to the country that deploys these systems. The US is debatably the world leader in stealth technology. Stealth technology is built around the principle of absorbing radio waves with unique materials that do not reflect microwave signals back to an enemy's radar.[M] Stealth technology built into aircraft like the F-22, B2, and others creates a very low radar signature typically masked by background noise that current radars have limited abilities to get through.[M] A quantum radar would likely have the ability to make out fine details of an aircraft through its ultra-high-definition radar picture.[H] (see figure 71) This would allow quantum radar operators to identify aircraft shapes and determine what type of aircraft was being identified.[M] Distinctively shaped aircraft like the F-35 would be identifiable by quantum radars.[M]

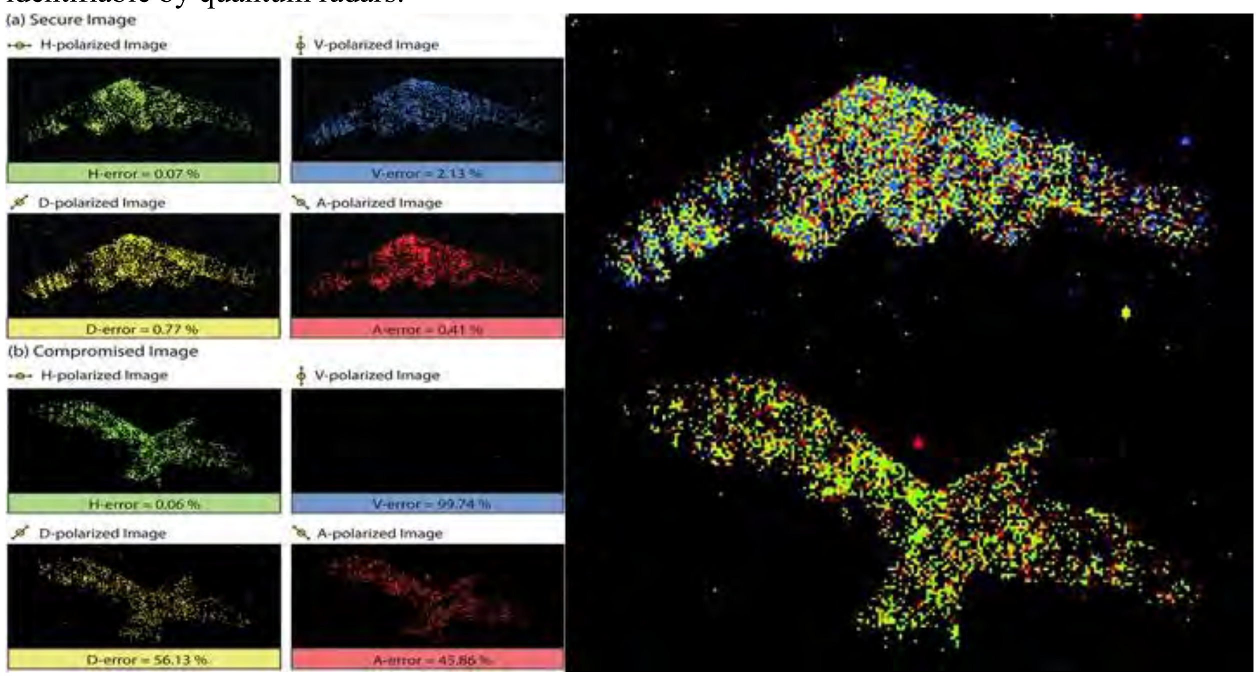

Figure 71: Image of possible quantum radar view of targets. (Courtesy of Fighter Jet World)

Quantum radar's other significant advantage over traditional radars is their low power emissions.[M] Current radar systems have largely remained unchanged since they were developed.[M] The likely development and deployment of quantum radars that are a low-powered system would increase their survivability because they become more challenging for adversaries to detect than conventional radar.[M] The other advantage that lower power emissions have for quantum radars is their possible use in the medical field.[M] The likely use for quantum radars in the biomedical field would revolve around their use as a non-invasively probe for objects with low reflectivity, such as cancer cells.[M]

China is investing heavily in quantum technology and is likely leading the world in quantum development.[M] While it is unlikely that China in 2016 was able to develop a functioning quantum radar, they likely are the best poised to develop and deploy an operational quantum radar by 2031.[M] This is a significant surprise as most of the development news around quantum radar development has been from western countries. China has invested nearly $10 billion into quantum research and development and recently opened the National Laboratory for Quantum Information Sciences in Hefei.[M] China's focus and leading-edge research will likely give them a significant advantage over other countries working in the quantum field, leading them to the development of deployable quantum radars sooner than other nations.[M]

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were generally reliable and tended to corroborate one another. Some articles pose a differing view of success in the field of quantum radars; however, the research done in this paper makes their view unlikely. There was adequate time, but the analyst worked alone and did not use a structured method. Furthermore, given the estimate's limited time frame, this report is sensitive to change due to new information.

Light Fidelity (LiFi) Technology Highly Likely Within 5 years

Executive Summary

With the introduction of Visible Light Communications (VLC)[21] technology along with the demand for faster internet speeds, lower latency, and greater bandwidth, it is highly likely that numerous companies will commercialize LiFi in the next five years. Although this technology is a promising means to communicate more efficiently, it is plagued with high costs and technological challenges associated with the characteristics of light. Still, it is highly likely that LiFi's increased bandwidth, speed, security, and complementary characteristics to WiFi, will drive the adoption cycle.

Discussion

LiFi is an alternative technology to WiFi designed to transfer data. It uses visible light of the electromagnetic spectrum between 400 THz and 800 THz for data transmission.M This is possible using VLC technology, which has two qualifying components: 1) at least one device containing a photodiode[22] to receive light signals; 2) a light source equipped with a signal processing unit for the transmission of signals.H LED light bulbs are the best VLC light source because they emit the extremely high rate of light required of a LiFi system, H and have high-quality illumination characteristics, as well. The structural principles of LiFi are like WiFi concerning access to the internet. It simply replaces WiFi's traditional router with an LED light bulb. As a result, several important characteristics emerge including increased speed, greater bandwidth, more security (see figure 72),H and interoperability. M

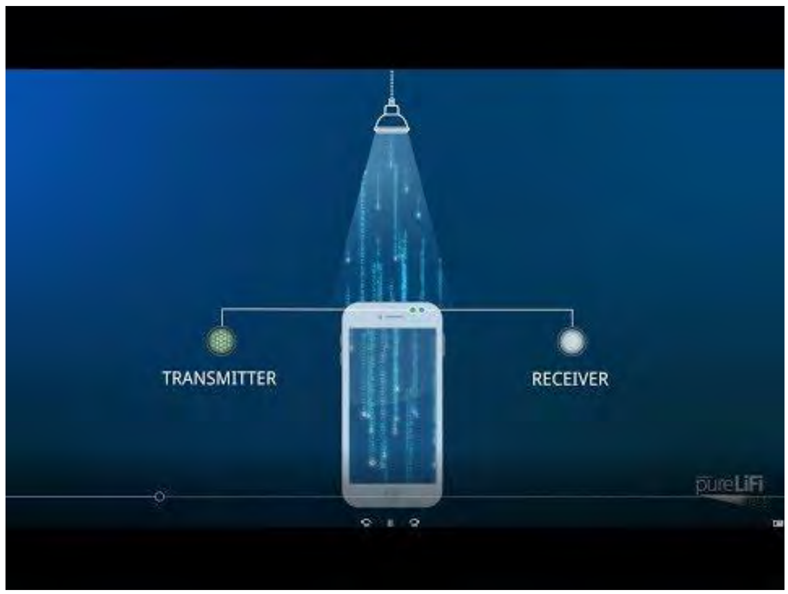

Figure 72: Video describing the qualities (speed, bandwidth, security) of LiFi Technology. (Courtesy of pureLiFi) To view click on the photo.

[21] Visible Light Communication is a technology that uses visible light, flicking on and off at imperceptible speeds to write and transmit data in binary codes.M

[22] A Photodiode is a semiconductor device that converts light into an electrical current.H

Feature	Li-Fi	Wi-Fi
Abbreviation	Light Fidelity	Wireless Fidelity
Function	It transmits data by using light with the help of LED bulbs.	It transmits data by using radio waves with the help of WI-Fi router.
Have some sort of interference or not?	Due to similar radio frequency waves there are no interference issues.	Have interference issues from nearby access routers.
Which technology is used?	Present IrDA complaint devices	WLAN 802.11a/b/g/n/ac/ad standard compliant devices
Speed of Data transfer	About 1 Gbps	WLAN-11n offers 150Mbps, About 1-2 Gbps can be achieved using WiGig/Giga-IR
Operational Frequency	10 thousand times frequency spectrum of the radio	2.4GHz, 4.9GHz and 5GHz
Intensity of Data	Work in high dense environment	Due to interference, work in less dense environment
Can cover distance up to	10 metres	About 32 metres (it may vary)
Privacy	Data can be transferred more securely as in Li-Fi light is blocked by walls	Some techniques are to be employed to secure data as RF signals cannot be blocked by walls in Wi-Fi technology
Applications	Used in airlines, undersea explorations, operation theaters in the hospitals, office and home premises for data transfer and internet browsing	Used for internet browsing with the help of wifi kiosks or wifi hotspots
Advantages of using these technologies	Due to less interference, it can pass through salty sea water and can also work in dense region	Due to interference it cannot pass through sea water and work in less dense region

Figure 73: Chart compares LiFi and WiF, including other qualities beyond speed, bandwidth, security, and interoperability. (Courtesy of www.jagranjosh.com)

Along with these superior characteristics (see figure 73), LiFi is bidirectional and full-duplex.[23][H] It is essential to distinguish between bandwidth[24] and spectrum[25] when discussing wireless communications. Visible light has a much wider bandwidth than WiFi, meaning that LiFi-enabled devices can simultaneously send and receive data at extremely high speeds, up to 224 gigabits per second.[M] At this speed, it would only take seconds to download a high-definition video.[H] The visible light spectrum is almost 10,000 times larger than the spectrum occupied by radio waves. [M] This attribute allows the light waves to carry far more information than radio waves.[H] . LiFi is argued to have better security than other wireless technologies.[H] Light does not go through walls, which means the wireless connectivity stays in the building.[H] WiFi, conversely, is prone to hacking as it has a broader reach where the radio frequency signal can penetrate walls.[M] Another feature of LiFi is that it does not interfere with radio signals. In contrast, WiFi interferes with the other nearby access points (routers).[M] Ed Huibers, the business developer for Signify(formerly Philips Lighting), says that "LiFi is a great alternative for WiFi, especially where radio waves are not permitted or work poorly, like on airplanes or in hospitals."[H]

Several countries were involved in LiFi research before 2011, with South Korea, the U.S., and Japan filing the most patents.[M] In the past ten years, however, the U.S. topped the patent list dwarfing South Korea, with China joining the group in third place.[M] There are strong indications that this technology will change future military operations. Frank Murphy, Mechanical Engineer at the U.S. Army Combat Capabilities Development Center, suggests that LiFi may be the perfect communications system, highlighting its

[23] Full-duplex is a type of communication in which data can flow two ways at the same time.[H]
[24] Bandwidth is the maximum rate of data transfer within a specific time frame. [H]
[25] Spectrum is a collection of waves with frequencies arranged in order.[H]

secure nature and line of sight (LOS) range; over 10 miles on dry land and over 100 miles in space.[H] The U.S. Navy wants to use LiFi technology to facilitate ship-to-ship communications at 12 nautical miles, evading adversaries' abilities to hack the beam of light.[H] Further, LiFi technology is highly likely to yield solid commercial interest in the next two to four years, especially as every light source can connect to the internet.[H] Li-Fi also solves the [network] congestion problem.[M] In wireless dead zones or places where numerous people try to use data-intensive applications simultaneously, LiFi provides increased bandwidth.[M] LiFi will likely become available to the general public in early 2022,[H] and in June of this year, a major LiFi Conference will discuss market development, applications, and standardization.[H] Professor Harald Haas, the University of Edinburgh engineer who coined the term LiFi, suggests that laser-based LiFi data rates will reach 100 Gigabits per second (Gbps) by early 2022 and hopes to propel LiFi to an eye-watering terabit per second by 2024 in preparation for 6G technology to take hold by 2030.[H] The current global market value of LiFi technology is $295 million and is likely to reach $4.1 billion by 2026,[H] and $8 billion by 2030.[H]

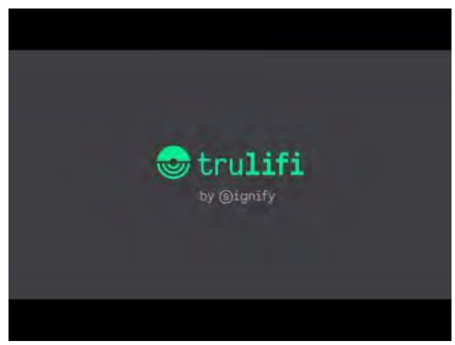

Figure 74: Video describing the benefits of LiFi Technology to future society. (Courtesy of Signify) To view click on the photo.

LiFi is costly. It will need reinvestment in lighting and wiring infrastructure to create a backbone network design.[M] LiFi components, infrastructure and numerous company use cases have significantly increased between 2017-2019.[H] Familiar names like Fujitsu, General Electric and Panasonic as well as newcomers like Lightbee, LumEfficient Lighting and Oledcomm are working to reduce production costs of LiFi components.[H] As the technology gradually takes hold, it will fuel new concepts like Industry 4.0 and flawless VR experiences (see figure 74).[H] A common misconception with LiFi is that it aims to replace RF wireless technologies like WiFi.[H] Despite this initial concern from telecommunication industry leaders, it will bring significant connectivity advantages and complement other wireless technologies.[H] To put this in practical terms, future smartphones and laptops will have multiple connectivity methods built-in, giving users the ability to seamlessly switch among LiFi, WiFi, and 5G/6G to take advantage of the best signal available at the time, operating in a wireless ecosystem. [H] Another common myth about LiFi is that if there is no visible light, then there is no signal. [H] Even if LiFi technology is dimmed low enough that a room appears dark, it will still transmit data.[H] Naysayers also suggest LiFi cannot work in sunlight. As tested by pureLiFi, it can operate in daylight and even in direct sunlight conditions.[H]

Analytic Confidence

The analytic confidence for this estimate is *high*. Most sources were highly reliable and very closely aligned with one another's analysis, notably as the research spanned the last decade. The analyst retains minimal knowledge on the subject, worked alone, and did not use a structured method. However, the analyst did confer with the instructor and the team regarding LiFi's rating as a surprise technology. There was adequate time to synthesize the information, and this analyst believes that the estimate is within the range of reasonable opinion. It is likely that new information will not change this estimate.

Synthetic Data Highly Likely Available Within 2 to 4 Years, Readily Available Publicly Between 2025 and 2030

Executive Summary

Artificially generated but statistically similar data sets, commonly referred to as Synthetic Data, are highly likely to enter production between 2023 to 2026 and will highly likely be available to the public and smaller companies at an affordable price and scale between 2025 and 2030. Algorithms generate artificially created synthetic data for model validation and AI learning systems. Synthetic data will eliminate bias and personally identifying sensitive data, reduce cost and the time needed to label the data, allow smaller companies to afford the information, and provide for a more robust AI development base. Synthetic data is not without issues. It fails to replicate the diverse situations found in real-world occurrences, and any error in the data set may drive an increased error rate in the output or produce a compromised outcome.

Discussion

Synthetic data is artificial data generated by computers versus collected through naturally occurring, actual world events.[H] Synthetic data has multiple uses in AI, machine learning, and training machine learning models.[H] The data contains all the characteristics of real data without any of the sensitive aspects of it.[M]

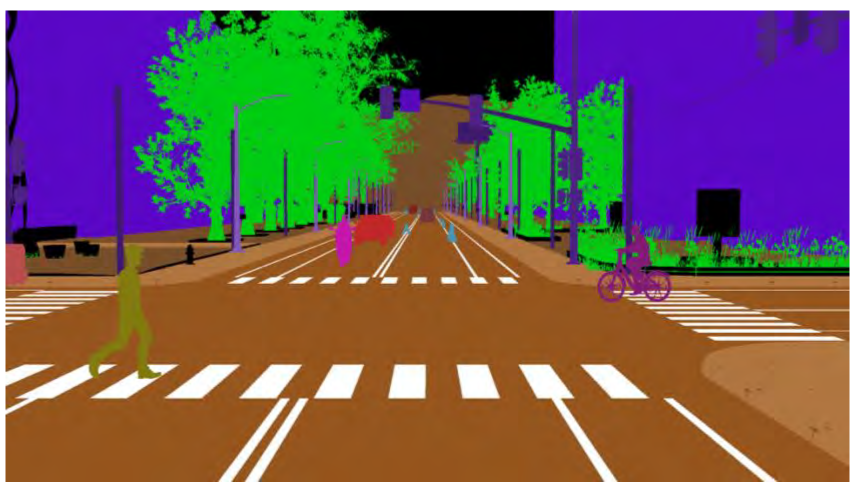

Figure 75: Synthetic Data generated image. (Courtesy of Logicai)

AI requires large amounts of data which needs to be unbiased and accurate.[M] Normally, AI learns through using “training data” in large quantities to reduce the error rate and increase the confidence levels.[H] It is widely accepted that the larger the dataset, the better the AI system will be at learning and recognizing the “item.” [H] Synthetic data is engineered to be more valuable than actual data by removing the sensitive information present in real data and eliminating the bias commonly present in real-world data.[M]

Synthetic data may solve problems that are unique to the AI environment. Some of the advantages of using synthetic data over real-world data are lower costs, scale, customization, and the ability to train AI to make decisions based on scenarios that are not likely to occur in a real-world setting.[M] Speed of processing is another major benefit to synthetic data over real data since the time required to label large amounts of data can be cumbersome.[H] A drastic example of the time and manpower needed to catalog and process data is highlighted by a Peoples Republic of China company using a staff of 300,000 Chinese workers tagging data full time, 24 hours a day, to feed machine learning and expand AI capabilities.[L] Real-world data is also expensive to collect, rendering smaller companies incapable of competing with larger multi-billion-dollar high tech and automotive companies.[H]

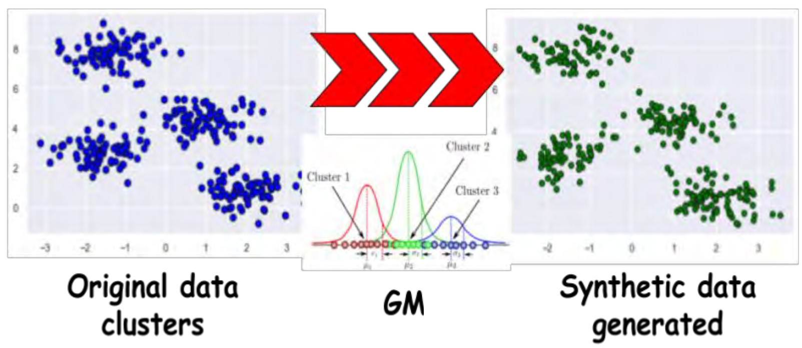

Figure 76: Synthetic vs real data cluster differences. (Courtesy of Towards Data Science)

Synthetic data has vulnerabilities and is not a perfect solution or alternative to real-world data. One downside to synthetic data is the "domain gap," or content gap, which is due to the synthetic data mimicking a limited set of "scenes" and not as diverse as the data sets found naturally in the real world.[M] Additionally, it can be complicated to produce high-quality synthetic data if the system or process is too complex.[M] Also, if the synthetic data is not identical to the real-world data, it can negatively impact the AI decision-making process or compromise the outcome. Synthetic data, while like real-world data, is not mathematically able to replicate it exactly.[H] Finally, there may be trends or outliers not represented in the synthetic data that are present in the real-world data.[M]

The international community is pursuing synthetic data research to further development efforts. China is aggressively developing an AI capability and is pursuing synthetic options to augment real-world data.[M] Academic and government research institutes, including the Chinese Ministry of Science and Technology (MOST), the Science, Technology, Innovations Committee of Shenzhen, and the Shenzhen Key Laboratory of Computational Intelligence in Southern University of Science and Technology funded research into synthetic data to further the AI development efforts.[M] Russian researchers at the Tomsk Polytechnic University in Tomsk, Russia, are working with synthetic data to help AI learn to detect road pavement cracks under a project funded by the Russian Foundation for Basic Research.[M] A research team from the K.J. Somaiya College of

Engineering, Mumbai, India, researched machine learning-based synthetic data generation and presented the findings at a conference in Coimbatore, India, in late 2020.[M] The widespread research into synthetic data may indicate how governments and industries will solve the problem of not having enough data to train AI and enhance machine learning.

Analytic Confidence

The analytic confidence for this estimate is *high*. Sources were generally credible and did not demonstrate any bias. The analyst did not collaborate with anyone and did not use a structured method. The topic matter was somewhat complex, but the research was basic and straightforward, and there were some time constraints on the assessment. Based on the speed and priority of the development, there is likely to be new information available in the foreseeable future. An update is not anticipated.

Utility Fog, or Foglets, Highly Unlikely Available Within 19 Years for Government or Military Use, Not Available for Commercial Use in Next 30 Years

Executive Summary

Utility Fog is highly unlikely to enter production by 2030 to 2040 and will not enter the commercial consumer market in the next 30 years. Utility Fog is a conceptual collection of networked robots on the nanoscale, gathering to change shape and properties based on user commands. Currently, chipmakers cannot manufacture processors small enough to integrate into the Foglets, and batteries on the nanoscale are still early prototypes.

Discussion

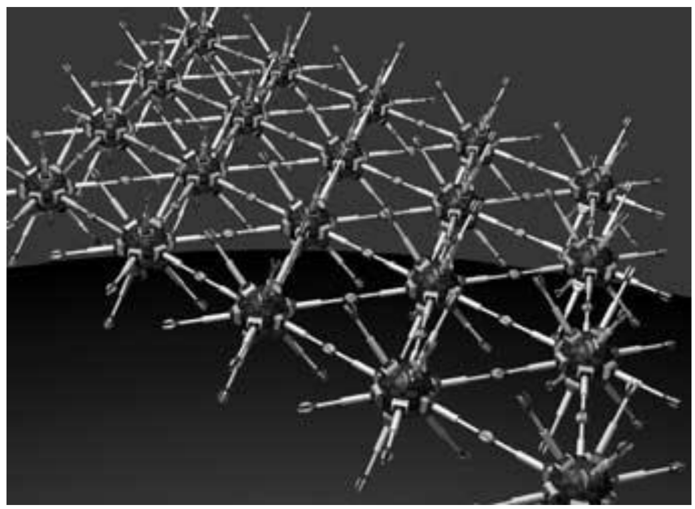

Figure 77: Artist's rendering of utility fog. (Courtesy of Researchgate)

The concept of Utility Fog was theorized and published by J. Storrs Hall in 1989. He envisioned groups of tiny, nanoscale self-replicating robots capable of assuming the shape and texture of whatever the controller desired.[L] The Utility Fog individually referred to as "Foglets", or individual nanorobots, is envisioned to measure 10 microns in diameter, be powered by electricity, and each possessing a small processor to control its actions.[L] Hall highlights the need for the Foglets to swarm at the nano level to actualize the Utility Fog concept.[M]

The development of Utility Fog is still very conceptual. An operational Utility Fog system is highly unlikely to be developed in the next 20 years, but the subsystems needed to build and compile the nanobots is being researched successfully. Two researchers at the National Institute for Materials Science in Japan reported the successful development of a "self organizing16-bit parallel processing molecular assembly." [M] The research was done in support of medical studies but applies to various fields using nanotechnology. This demonstrates the ability of a central molecule to make decisions for 16 other "machines" simultaneously using a scanning microscope.[M] Researchers in Germany at the Max Planck Institute for Solid State Research also made progress in organizing molecules into nanostructures. [M] The researchers created a "surface slime" with molecules having predetermined functions that self-organized into nanostructures.[M] The ability to "swarm" is needed for a successful Utility Fog system to operate cohesively.[M] Extensive research is being conducted and demonstrated at various universities, and the ability to field a "swarmable" system is not a limiting factor for Utility Fog development.[M] Researchers from the China Academy of Sciences, IBM, Columbia University, and Soochow University successfully constructed a nano-turbine from graphene and a carbon nanotube.[M] The nano-turbine is driven by fluid flow versus airflow and designed under the auspices of biomedical research, but the technology proved a propulsion device is possible at the nano level.[M]

Figure 78: Artist's rendering of an individual nanobot. (Courtesy of Wordpress)

The development of nano-sized components is essential to being able to field a Utility Fog system or network. Nano-sized processor technology is required to enable a Utility Fog fleet and will limit when the technology is available.[M] IBM is working on miniaturizing their processors and developed a microprocessor that is smaller than a grain of salt and cost less than 10 cents to manufacture.[H] One issue of reduced size microprocessors and nanoscale transistors is the problem of electron tunneling, which occurs when the nanomaterial is too thin, and the electrons move through the material versus the transistor controlling the flow of electrons.[H] This effect does not allow the transistor to control the electrons and renders the processor useless.[H] The batteries required to power the nanoscale devices are in the prototype phase.[M] While further along than the nanoscale processors, they are not ready to be integrated to power the devices.[M] Researchers have developed various devices at a scale larger than acceptable for Utility Fog, and reducing the size and cost are proving difficult to overcome.[M]

Analytic Confidence

The analytic confidence for this estimate is *high*. Sources were generally credible and did not demonstrate any bias. The analyst collaborated with teammates and did not use a structured method. The topic matter was basic, but the research was somewhat complex, and there were some time constraints on the assessment. Based on the speed and priority of the development, there is not likely to be new information available in the foreseeable future. An update is not anticipated.

Alcubierre Warp Drive Highly Unlikely Operational For Decades

Executive Summary

The Alcubierre Warp Drive is highly unlikely to be operational for decades. Despite the recent discovery of gravitational waves, and continued NASA studies, the warp drive is still just a theory which requires additional discoveries to make it a reality. The ability to build an operational warp drive requires advances in technology in the fields of quantum physics, quantum mechanics, metamaterials, and energy.

Discussion

Albert Einstein's Theory of General Relativity provided an understanding of mass and energy and how the force of gravity creates ripples or waves in the space-time continuum.[H] In 1994, Miguel Alcubierre proposed a mathematical model which in theory would allow faster than light space travel. "To put it simply, this method of space travel involves stretching the fabric of space-time in a wave which would (in theory) cause the space ahead of an object to contract while the space behind it would expand. An object inside this wave (i.e. a spaceship) would then be able to ride this region, known as a "warp bubble" of flat space."[H] (see figure 79)

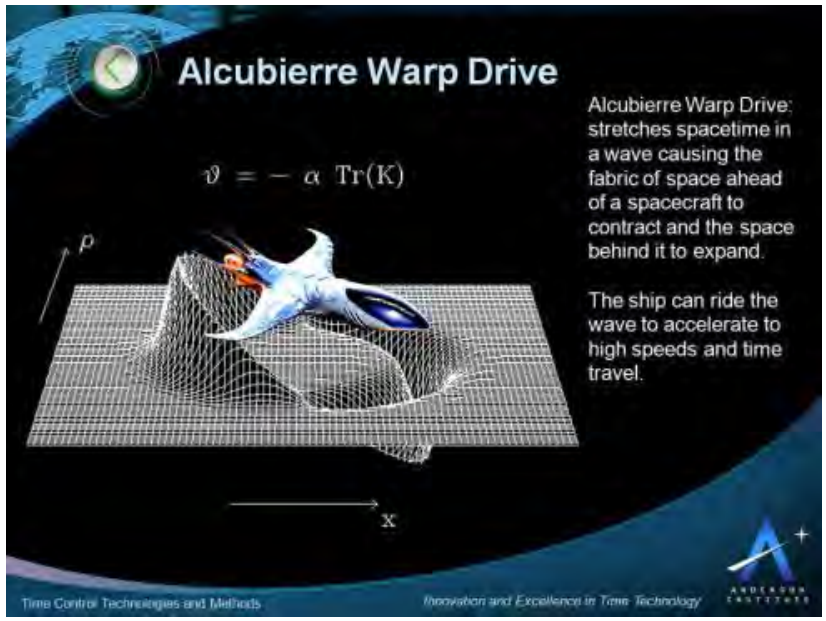

Figure 79: Alcubierre Warp Drive depiction. (Courtesy of Anderson Institute)

The Alcubierre Warp Drive starts with math, which must then be proved possible by physics, before it can move to a working model.[H] Dr. Harold "Sonny" White published a paper in 2011, in which he describes the requirements to prove the physics necessary for the Alcubierre Warp Drive theory.[H] In 2012, NASA began working on an Alcubierre Warp drive engine, which would reduce the energy requirements.[H]

On August 14, 2015, the Laser Interferometry Gravitational-Wave Observatory discovered gravitational waves created by two colliding black holes.[H] This discovery is important as it provides proof of ripples in the space-time continuum.[H] (see figure 80) This finding confirmed Albert Einstein's Theory of Relativity, and offered the possibility of proving the Alcubierre Warp Drive theory.

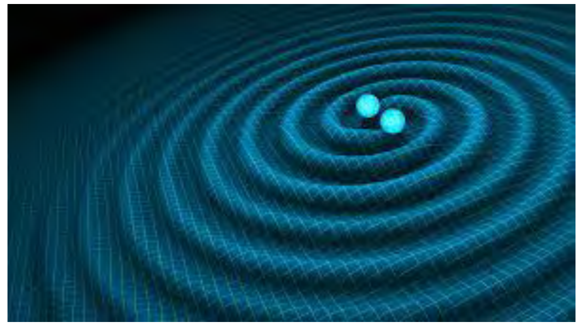

Figure 80: Gravitational waves depiction by NASA. (Courtesy of NASA.gov) To view a video depiction go to: https://youtu.be/zLAmF0H-FTM (Courtesy of LIGO Lab Caltech : MIT)

In 2019, Joseph Agnew from Huntsville's Propulsion Research Center, presented the results of his study in which he discusses how advances in warp drive theory, along with technology advances, increases the feasibility of discovering a solution to an Alcubierre Warp Drive.[H] A recently published paper, which is still not peer-reviewed by Bobrick & Martire discusses physical warp drives.[H] Sabine Hossenfelder, a theoretical physicist, describes the paper as including the geometry of warp drives, and demystifying the warp drive theory, while providing a mathematical basis for further study.[M]

Despite the recent advances in mathematics and physics in providing proof of the feasibility of the Alcubierre Warp Drive, it will take major advances in technology to reach a point where it can be proven and operationalized. A warp drive requires vast amounts of energy to work, possibly even dark energy, which researchers do not understand what it entails.[H] The current advancements in quantum physics, quantum mechanics, metamaterials, and energy are encouraging, and make the idea of faster than light travel a possibility.[M] The feasibility of an operational warp drive is in the far future.[H]

Analytic Confidence

The analytic confidence for this estimate is *high*. Sources were generally reliable and tended to corroborate one another. There was adequate time, but the analyst worked alone and did not use a structured method. Furthermore, given the lengthy time frame of the estimate, this report is sensitive to change due to new information.

Convergence of Neuromorphic Computing, Synthetic Data, and Bio-nano Technologies Likely Available Within 9 to 14 Years, Not Available for Commercial Use Until After 2040

Executive Summary

The convergence of neuromorphic computing, synthetic data, and bio-nano technologies is likely to occur between 2030 and 2040 and advance data production and management, nanotechnology, and neuromorphic computing leading to the “Internet of Bio-Nano Things”. The additional integration of biodegradable sensors and triboelectric nanogenerators will further enhance the systems. Additional advancements and novel use of the technology will challenge and counter the US during competition and in conflict across domains. Challenges still exist to achieve the convergence: operating at the nano level, the resistance of industry to shifting to neuromorphic computing over the von Neumann architecture, ethical issues, and communications challenges are all potential roadblocks.

Discussion

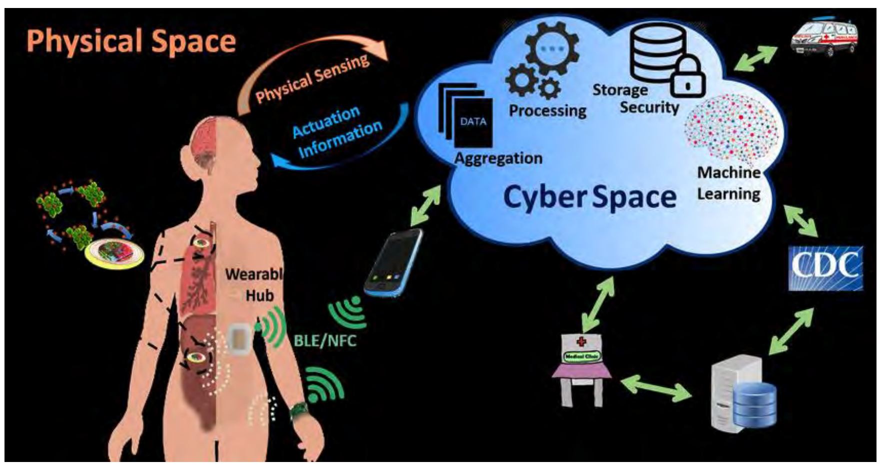

Figure 81: Concept of Internet of Bio-Nano Things (Courtesy of IEEE Access)

The ability to converge bio-nano devices capable of communicating with one another and their surroundings by using a deep learning platform, educated through processing large amounts of synthetic data, and fielding a “Bio-Nano Internet of Things” or “Internet of Bio-Nano Things” (IoBNT) poses leapfrog advancements in the fields of medicine and individual performance enhancement.[M] A critical element to the IoBNT is establishing a Brain-Machine Interface (BMI) to conduct the interactions with a neuromorphic system, enabled by a wireless signal, to provide direct interactions between users and neural networks.[M] The establishment of an IoBNT tied into a neural-based wireless network acting as an artificial brain is one example of an endless list of applications the technologies offer. The convergence of neuromorphic computing, synthetic data, and a bio-nano infrastructure will provide an infinite stream of information in multiple scenarios ranging from medical applications to soldier and pilot performance to intelligence collection activities.

The convergence of bio-nano, neuromorphic computing, and synthetic data yields endless possibilities for machine learning and technology integration in ways not previously utilized. The combination of technologies is conceptual, and research is underway with convergence likely between 2030 and 2040. Numerous countries are researching the bio-nano field, with China, the US, and India publishing the most research on the topic.M

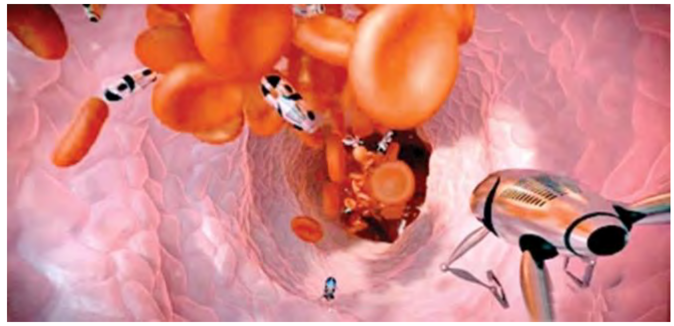

Figure 82: Concept of Bio-Nano Robots (Courtesy of Daily News)

Companies and academic institutions are researching bio-nano systems, including Oxford Nanopore Technologies, Nantero, Liquidia Technologies, DigiLens, and Albionic. The five companies alone received over $200 million in funding in 2018 for medical and exquisite applications across the spectrum.H Neuromorphic computing is advancing at a high rate of speed as well with Alphabet, Apple, Arm, Intel, and Nvidia leading the field in research and development.M Synthetic data is also receiving significant investment and attention by industry, and one that will bring neuromorphic computing to reality with DataGen, Cvedia, Hazy, AIReverie and ANYVERSE leading the new companies.M

The development of biodegradable sensors, carbon nanotubes, and triboelectric nanogenerators and the convergence with bio-nano, neuromorphic computing, and artificial data are likely to make the IoBNT and other self-contained systems possible. Gartner identified biodegradable sensors as one of five emerging trends for the next 10 years.H[26] Industry is aggressively pursuing biodegradable sensors, and the US Food and Drug Administration approved an implantable sensor already, leading to the potential widespread use in the future.H[27] The sensor is not on the nanoscale at this time, but it is a proof of concept for a biodegradable sensor implanted in the

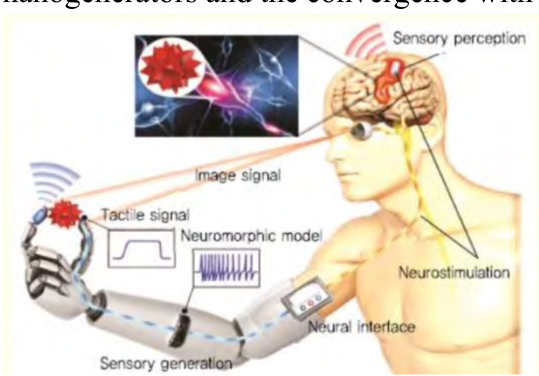

Figure 83: Concept of IoBNT (Courtesy of Electronics and Telecommunications Trends)

[26] Jo Ann Dempsey, Short Form Analytic Report, "Medical Biodegradable Sensors Almost Certain Within 10 Years, Field Deployable Between 2032-20137"
[27] Jo Ann Dempsey, Short Form Analytic Report, "Medical Biodegradable Sensors Almost Certain Within 10 Years, Field Deployable Between 2032-20137"

body.[H28] CNT show a wide range of properties and are popular for use as biosensors.[M29] Triboelectric nanogenerators are likely to provide the answer to power generation for the contained systems. TENGs use small-scale mechanical (friction and static-based) energy to produce electricity.[H30] There are four modes of TENGs that allow for diverse application from harvesting wind,[H] to harvesting blue energy[H], to harvesting human-created energy.[H31] One of the aspects that makes triboelectric nanogenerators so appealing are the many sources from which the mechanical energy derives: human body movement, the rotation of tires on vehicles, wind, or wave motion, to name a few.[H32]

One of the challenges to the convergence and development of a system using bio-nano, neuromorphic computing, and synthetic data is the development of reliable models and simulation environments, both physical and cyber, to mimic and capture the testing data accurately.[M] An additional challenge to the convergence is the resistance, and potential compatibility issues associated with moving away from a von Neumann architecture to one neuromorphic in nature.[M] Most conventional computers and mobile devices available use the von Neumann architecture. The shift to a model that may not be compatible may be problematic and drive the need for additional hardware and software interfaces.[H] The question of regulation of the convergence of the technology is an issue as well and possibly a roadblock to innovation.[H] When does self-regulation of science turn into a state responsibility to monitor and create policy for the good of the public?[H] Will strict regulations limit a country's ability to innovate and push the boundaries while a state with less ethical lines pushes the envelope and leads development in ways not acceptable to other countries?[H] Additionally, researchers at Georgia Tech highlighted the new bio-nano organisms could become a threat to the host, and even act as a pathogen driving the need for a potential "kill switch" to neutralize the bio-nano device in the event something goes wrong.[M] Another obstacle is the challenge of communication with the nano devices and how to balance short, medium, and long-range communications and how to map the molecular communications system.[M] Finally, the bio-cyber interface and the challenges associated with the bio-nano network is still an issue and is a roadblock to realizing the potential of the concept.[M]

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[28] Jo Ann Dempsey, Short Form Analytic Report, "Medical Biodegradable Sensors Almost Certain Within 10 Years, Field Deployable Between 2032-20137"
[29] Andy Pannier, Short Form Analytic Report, "Carbon nanotube transistor technology is highly likely to be used in military radio and communication platforms by 2030"
[30] Andy Pannier, Short Form Analytic Report, "Triboelectric nanogenerators likely to reach commercial production by 2027"
[31] Andy Pannier, Short Form Analytic Report, "Triboelectric nanogenerators likely to reach commercial production by 2027"
[32] Andy Pannier, Short Form Analytic Report, "Triboelectric nanogenerators likely to reach commercial production by 2027"

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were generally credible and did not demonstrate any bias. The analyst collaborated with teammates and drew from additional analytic products. The topic matter was complex, but the research was somewhat basic, and there were strict time constraints on the assessment. Based on the speed and priority of the development, there is likely to be new information available in the foreseeable future. An update is not anticipated.

Mind Control and Two-way Brain Computer Interface Technologies Likely Available For Human Use by 2030

Executive Summary

The convergence of optogenetics, neural lace, and bio-nano technologies is likely to occur by 2030. The additional integration of biodegradable sensors, carbon nanotube transistors, and triboelectric nanogenerators further enables these systems. The advancements in 4D printing and LiFi by 2030 will likely speed up the production. This convergence allows for human performance enhancement. The backbone for brain computer interface technologies is not developed yet, it requires a 6G network to use on a commercial level scale. In addition to the network architecture, challenges continue to exist in convergence of these technologies, there are ethical and legal issues that must be overcome to move from BCI as medical treatments to BCI as person enhancements.

Discussion

Brain computer interface (BCI) technology is a topic of much research. From use as medical implants for controlling thought processes, to interacting with and staying in front of artificial intelligence, BCI technology has a vast array of application both in the civilian commercial sector and in the military. No one device will define BCI, rather the convergence of multiple technologies will create the conditions for BCI to be producible, affordable, efficient, and effective.

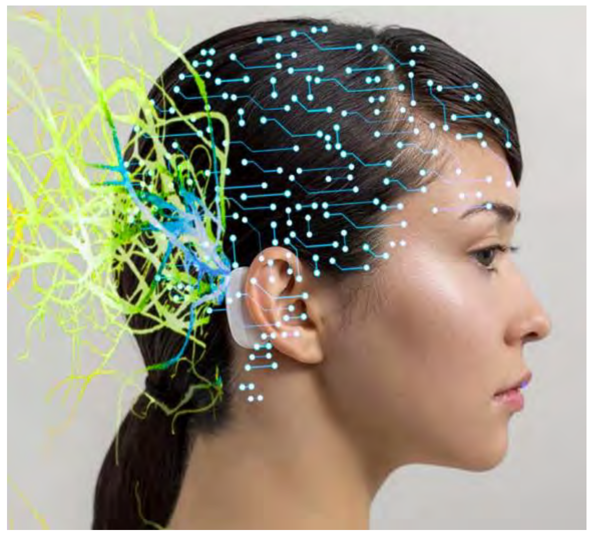

Figure 84: Concept of wireless neural lace. (Courtesy of Toby Weston)

Some research focuses on non-invasive BCIs, such as an exocortex. An exocortex is device, external to the brain that allows the computer and person to come together to produce a hybrid intellect.[33] [M] The exocortex is emplaced or removed at will. Other technological researchers study invasive devices, such as optogenetic implants, neural lace, or nanorobots. These devices are implanted in the brain through surgical means,[H] injection,[H] or

Figure 85: Ray Kurzweil discusses BCI. (Courtesy of YouTube) To view click on the photo

[33] William Snook, Exocortex Will Likely See Application Between 2030 and 2040

introduced through the blood stream.H One limiting factor to the current BCIs used for such illnesses as Parkinson's and epilepsy is that the devices are connected to wires that feed information from the brain to the computer. Researchers are working to develop wireless devices that communicate to the computer or cloud system, and in the case of neural lace (see figure 84), a wireless device that functions two ways, the brain "learns" from the computer and the computer "learns" from the brain.M These implanted devices allow external stimuli, whether it be lightH, chemical, or even electronsM moving through the cloud to control or influence human thought. Ray Kurzweil, a well know futurist, predicted that technologies such as neural lace and nanorobots will be available for use in humans by 2030 (see figure 85).

Another developing technology will likely provide power to these wireless implants within the human body. TENGs create electricity from subtle movements that create static and friction. Researchers demonstrated "a simple, low cost and effective approach of using the charging process in friction to convert mechanical energy into electric power for driving small electronics." H Advances made in the small-scale production of TENG clothing generate electricity to power sensors on the body or in the clothing.H Scientists continue to research the development of clothing TENGs that will provide enough power to recharge devices and store energy on the body. H In addition to the potential to provide power for the BCIs, TENGs are highly likely to power biodegradable sensors within the body. Powering the devices within the body is one hurdle to overcome, another is transmitting the information out of the body to a cloud or computer.

CNTTs provide a solution to a device small enough to be coupled with a BCI device and implanted inside the body with minimal energy input required to operate it.H These CNTTs communicate data out from the body to a cloud or computer. To do this at the level of commercial use worldwide, a more powerful internet network will be necessary. The network is the 6G network, predicted to be developed by 2030.H To keep up with the exponential increase in data exchanged across the wireless internet, to include data flows from medical implants, the 6G network must allow for more and faster data transfer rates than are available through WiFi.H LiFi is likely to be a solution to handle the data flows necessary of a 6G network.[34] H In addition to increased data flow rates, the 6G network provides greater security over previous "G" networks (see figure 86).H LiFi is currently more expensive that WiFi, but predicted to decrease in cost over time of development. H Another developing technology that is highly likely to decrease costs for human enhancement devices is 4D printing.

[34] Johnny Casiano, Light Fidelity (LiFi) Technology Highly Likely Within 5 years

4D printed products have two elements instead of one used in 3D printing: the rigid layered 3D structure (this is the product of 3D printing) and a geometrically coded flexible 3D structure.[H] 4D printing will allow

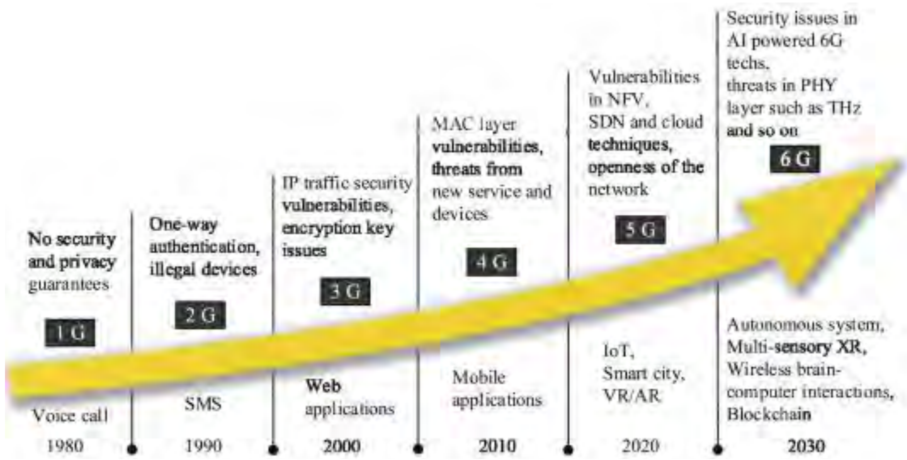

Figure 86: Advances in data flow and security across the "G" networks. (Courtesy of School of Computer Science, University of Technology Sydney)

for a decrease in production cost, similar to what is seen in 3D printing currently, as it is further developed and commercialized.[M] 4D printing research is actively pursuing 4D printed devices to be implanted in the human body.[H] This research coupled with BCIs, CNTTs, and TENGs is highly likely to develop low-cost implants, that can be powered from the body and provide two-way communication between humans and artificial intelligence across the internet, between 2030-2040.

Western societies continue to see limitations in the development of BCIs based on ethical issues and regulatory requirements.[H] This prolongs industrialized production of these technologies. These same restrictions do not apply to the development and use of these technologies in authoritarian societies such as China and Russia.

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were reliable and tended to corroborate one another. There was adequate time, but the analyst worked alone and did not use a structured method. However, the analyst collaborated with the team on the possible convergences of technologies discussed. Given the lengthy period of the estimate, some technologies in this report are sensitive to change due to new information.

Multiple Technologies Regarding the Control of Light Likely to Come Online Between 2026-2040

Executive Summary

This research project focused on five exciting technologies, including Digital Telepathy, Volumetric Display Technology, LiFi Technology, Light-bending Metamaterials, and Parallel Reality Technology. Apart from digital telepathy, each of the technologies has unique characteristics regarding light (or the control of light). The five technologies all have various governments, industries, and academic institutions concentrating resources into their development, with some undergoing current beta testing in commercial settings. Despite ethical and technological problems surrounding these exciting technologies, all five will likely proliferate in commercial sectors, with apparent follow-on military use, between 2026 and 2040. Further, these five technologies will likely provide for convergences in military relevant ways within the same timeframe.

Discussion

Regarding the broad considerations of these five technologies, a few aspects are immediately apparent. Two of the technologies seem to operate directly contrary to each other, warranting greater investigation into their opposing light characteristics. Parallel Reality Technology emits every color on the visible light spectrum simultaneously to target multiple people with different information from the same platform.[35] In contrast, light-bending metamaterials' physics attempts to bend from view every incoming light wave on the visible light spectrum to make an item appear invisible.[36]

Volumetric Display Technology, Parallel Reality Technology, and LiFi are likely to converge for advertising purposes initially but will likely graduate toward in-theater camouflage for military use by 2035. Samsung expects that mobile and larger displays will begin to display actual volumetric holograms, requiring at least 580 Gigabits per second for a phone-sized 6.7-inch display, and “human-sized” holograms at several terabits per second.[H] It is also likely that the defense industry will layer these technologies with Light-bending Metamaterials, to facilitate large scale deception operations using camouflage alongside optical cloaking capability (invisibility) across expansive geographies by 2040. Recently, a team of scientists demonstrated successful methods for temporal invisibility.[H] Each year, scientists improve upon the technology of metamaterials, remarkably engineered coatings, devices, and components.[H] Considering deception operations, it is likely that Volumetric Display Technology and LiFi will deliver the preponderance of next-generation sensor defeat capability missing only a

[35] Reference Parallel Reality SFAR by Col Johnny M. Casiano

[36] Reference Perfect Light-bending Metamaterial SFAR by Col Johnny M. Casiano

small, tangible object to deliberately create a heat signature, radar signal, or sonar feedback.

Digital Telepathy Technology is likely to surface commercially in the next decade, mainly because of 6G wireless technology providing the requisite capacity and capability and humans' inescapable need for the convenience and efficiency of digital communication. The Internet of the Body (IoB) will safely and securely link implant devices such as pacemakers, gastrointestinal pills, and in-brain devices.H

The convergence of these technologies will require at least four conditions to exist. The four conditions include a fully operational 6G technology, mastery of the terahertz regime of the electromagnetic spectrum, the prolongation of Moore's Law, and cost-effectiveness. 6G technology is chief among these conditions. It must be completely operational (likely by 2030) to enable a fully digital and connected world.M The main objectives for 6G systems are extremely high data rates per device, a very large number of connected devices, global connectivity, very low latency, lower energy consumption with battery-free internet of things devices, ultra-high reliable connectivity, and connected intelligence with machine learning capability.M All of these characteristics (either individually or in combination) will facilitate the convergences discussed earlier. There are also additional requirements connected to the presupposed application of 6G technology. Engineers will need to figure out material solutions to create even more massively dense antennas, improve radio wave spectrum efficiency, and handle other novel or semi-novel issues introduced with terahertz waves[37].H Metamaterials have emerged as an attractive option for addressing many of these issues and have become a useful tool in optics and electromagnetics to construct devices with complex spatial- or frequency-domain behavior. H

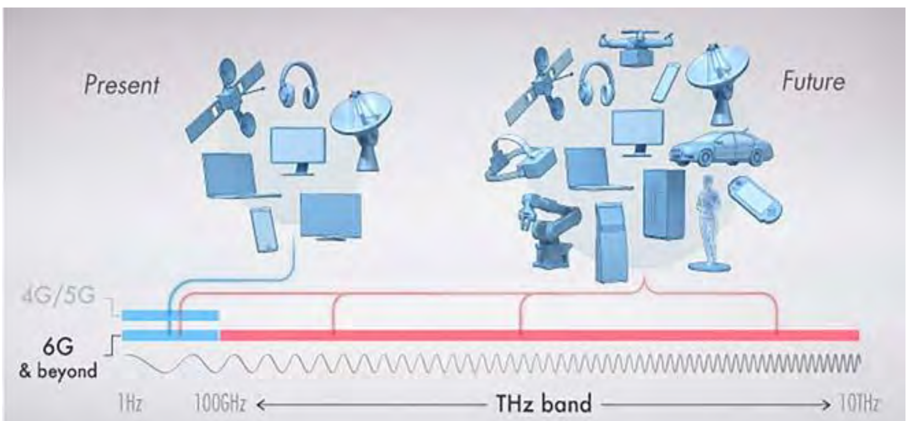

Figure 87: Picture showing the promising role of the terahertz regime on the electromagnetic spectrum tied to the introduction of 6G wireless technology. (Courtesy of IEEE Open Journal of the Communications Society)

[37] Terahertz waves are generally defined as the electromagnetic spectrum region in the range of 100 GHz (3 mm) to 10 THz (30 μm), which is between the millimeter and infrared frequencies.

Terahertz band communication will likely be a key enabler in the post 5G era at both the device access and network level.[H] Due to the versatile properties of the THz links, they are likely to play a pivotal role in the upcoming 6G wireless mobile communications.[H] The terahertz segment of the electromagnetic spectrum offers vast potential for high data transmission rates.[M] The currently available data rates constrain the available bandwidth, and the terahertz frequencies offer wide bandwidths in an uncrowded part of the electromagnetic spectrum (see figure 87).[M] The THz frequency band assures extensive throughput, theoretically extending up to several THz leading to capacities in the order of Terabits per second (Tbps).[H] However, the terahertz band is the dark horse of the electromagnetic family.[H] It is not as well-known as radio or microwaves, and there are fewer devices able to control the wavelength.[H] Of the four significant technological advances,[H] identified as future directions for the integration of THz links in 6G communications, two reference the analyst's technologies discussed herein: holographic communication (Volumetric Display Technology) and reconfigurable intelligent surfaces (Light-bending Metamaterial).[H]

Figure 88: Marc Andreessen, entrepreneur, investor, and software engineer, convincingly argues that although Moore's Law is coming to an end, there are still decades of computer processing advances ahead, using alternative methods (Courtesy of AH Capital Management) To view click on the photo.

Alongside 6G technology is the need to prolong Moore's Law.[38] Chip manufacturers may find it more challenging to move to a 3nm scale and smaller towards the middle and end of this decade.[H] Computer chips are already at the sub-atomic level. Moore's Law is likely to fail before 2030.[H] Marc Andreessen, a co-founder of Netscape and co-founder of Silicon Valley Venture Capital Firm, is an American entrepreneur, investor, and software engineer. He suggests that there are decades of advances to be made despite dependence on Moore's Law (see figure 88).[H] Alternative methods to offset the diminishing effects of Moore's Law include scaling up to use of multiple chips (or cloud-based computing), the use of specialized chips, like those used in neural networks, the incorporation of artificial intelligence, and optimizing the software to realize greater efficiencies with current chips.[H]

[38]Moore's Law suggests that approximately every two years, there is a "doubling effect" that results in faster, cheaper, and more power-efficient computer chips.

The last condition that must exist for these technologies to converge is that their development must become cost-effective. Most are in the R&D stages or nascent stages of development, still moving from theoretical models to application at scale. Additionally, the infrastructure necessary to build at scale has likely not yet been developed. This fact alone will exponentially increase the cost to bring the product to market, further hindering the opportunity for a convergence. One of the main reasons technology becomes less expensive over time is the competition from other countries.[M] While most technology has commercial uses, the five technologies researched in this report have clear national security implications. Technology with these qualities will not foster collaborative efforts between competitor governments.

Analytic Confidence

The analytic confidence for this integrated estimate is *moderate*. This estimate introduced additional resources, but the majority remained the same from previous reports. They were very reliable and tended to corroborate one another. The analyst identified similarities across technological domains that fed into the likelihood of convergences discussed in the estimate. There was adequate time to synthesize the information provided by the previous five estimates, and the analyst believes this estimate lies within the range of reasonable opinion. Given the timespan for these technologies to reach maturity, their subsequent application within the commercial sector, and the predisposition for convergences in military relevant ways, it is likely that new information will change the estimate.

China is Highly Likely to Use Five Surprise Technologies in the Next 10 Years to Expand Its A2AD to the Point of Negating US Capabilities

Executive Summary

China is highly likely to use unsinkable metals, homomorphic encryption, quantum radars, neuromorphic computing, and exocortexes together to create an Anti-Access/Area Denial (A2AD) network that is impenetrable in the next 10 years. China's leveraging of a nationalistic future warfighting concept, state focused academia, and robust military industrial complex enables them to likely make leapfrog steps in technology that will strategically give them an advantage in the future global competitive environment. Despite the US and other western nations' lead in developing some of these technologies, China will likely prevail in bringing them to military use before any other nation giving them a significant strategic advantage.

Discussion

China is following a future warfare concept titled Intelligentized Warfare.[H] This concept emphasizes emerging technologies such as artificial intelligence, cloud computing, big-data analytics, quantum information, and unmanned systems as driving components.[H] China has the political, military/state industrial base, and strategic focus to effectively bring these systems together.[M] Inside of this warfare concept, China is highly likely to bring together quantum radars, homomorphic encryption, neuromorphic computing, exocortexes, and unsinkable metals to create an A2AD network that cannot be penetrated in the next 10 years.

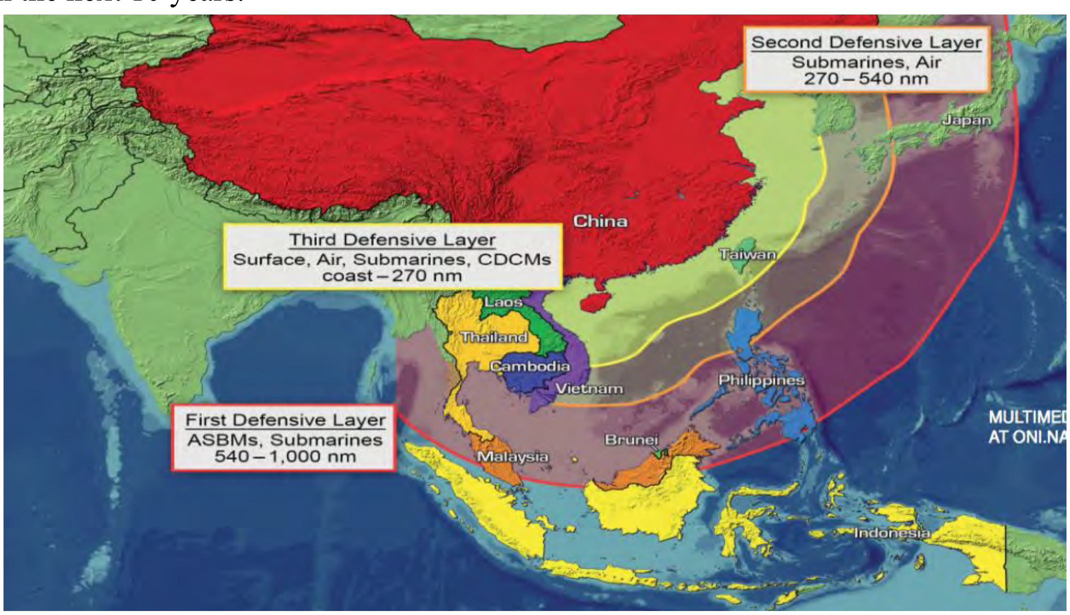

Figure 89: China's A2/AD bubble in the South China Sea and the Pacific Ocean. (Courtesy of Missle Defense Advocacy Alliance)

China has taken on a nationalistic approach to future global competition by placing emphasis on leveraging science and technology to advance its military. For the past several years, China has been pursuing a new military concept of war titled Intelligentized Warfare.[H] This new strategic concept involves the development and operationalization of artificial intelligence and the enabling and interrelated technologies required for its realization for military applications.[H] The concept of Intelligentized Warfare has developed from previous concepts like mechanization and informatization. Intelligentized Warfare is not just about AI but brings together the operational force consisting of people, weapons, equipment, and ways of combat.[M] This new concept builds on a premise of intelligent weapons and a new military system of systems that involves human-machine integration and AI in a 'leading' military decision-making role.[M]

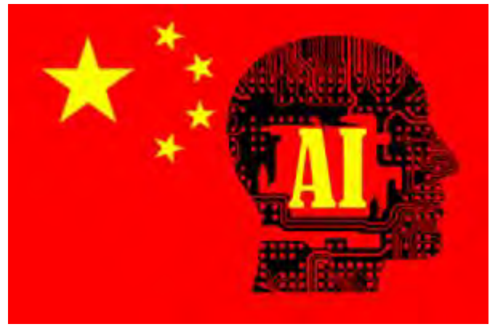

Figure 90: "Intelligentization" and a Chinese Vision of Future War. (Courtesy of TRADOC Mad Scientist Blog)

In addition to developing a national warfighting concept strategy, China has taken on some other major improvements to compete globally. The first central area of

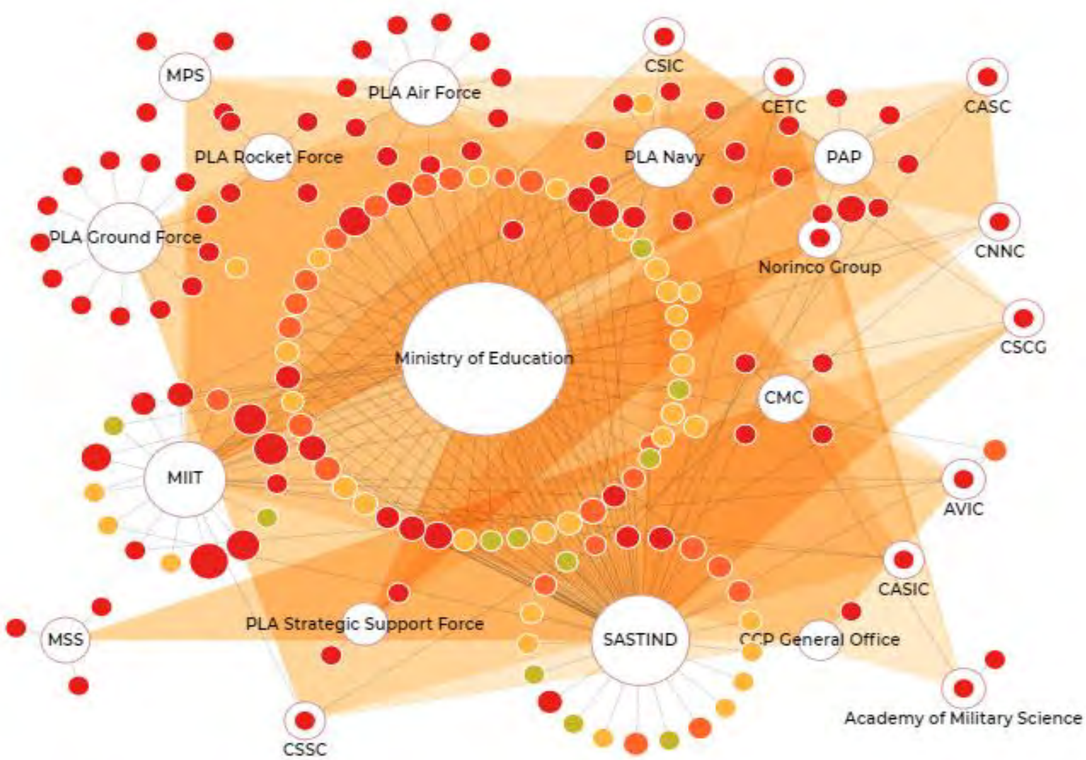

Figure 91: China Defense University Tracker (Courtesy of Australian Strategic Policy Institute)

development is in the academic arena. China has invested billions of dollars into its military/state academic structure. The Chinese leadership has explicitly mentioned the need to have an academic structure that will bring to the forefront Intelligentized Warfare's concept.[H] The Peoples Liberation Army is determined to use this academic base to seize the initiative in future strategic technologies to out compete everyone in future wars. Figure 91 shows a study completed by the Australian Strategic Policy Institute that demonstrates the amount of interaction between the military and state academic systems. In further research by the Australian Strategic Policy Institute, they broke out the areas of focus that these academic institutes are concentrating on and how much of their efforts are going into specific research areas that support Intelligentized Warfare. A specific example of China's push to develop their academic base to support

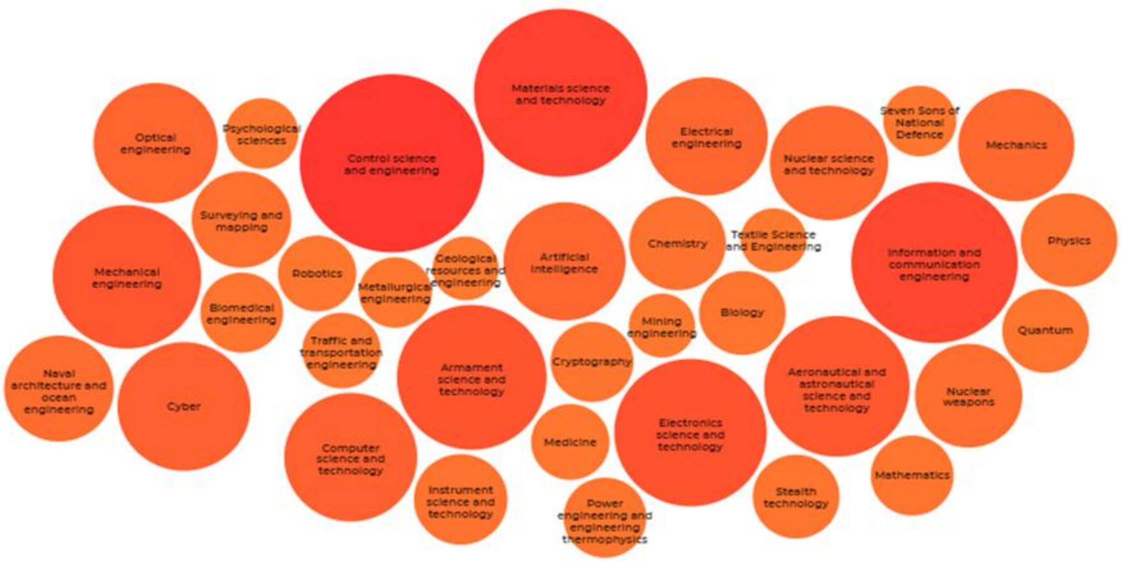

Figure 92: Fields of China's Defense Industry. (Courtesy of Australian Strategic Policy Institute)

their future warfighting concept is the investment of nearly $10 billion into quantum research and development at the recently opened National Laboratory for Quantum Information Sciences [M]

The final area of investment that China is making in their future warfighting concept is their military-industrial base. Upgrading equipment and technologies have been an ongoing priority for China. From 2010 to 2017, China's annual spending on military equipment rose from $26.2 billion to $63.5 billion.[H] According to the Stockholm International Peace Research Institute Arms Industry Database, at least four of China's primary arms companies rank among the world's top 25 in 2019. They include Aviation Industry Corporation of China, CETC, China North Industries Group Corporation, and

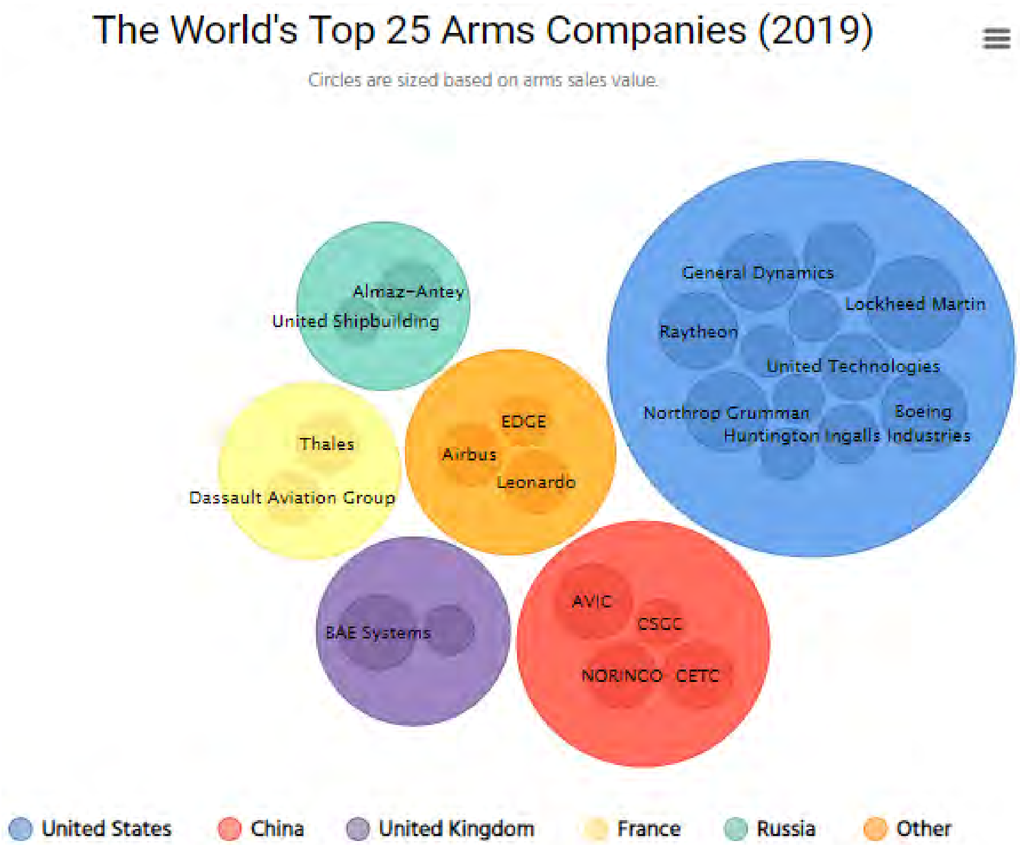

Figure 93: China Power Project, Distribution of Arms Companies. (Courtesy of CSIS Center for Strategic & International Studies)

China South Industries Group Corporation.[H] Figure 92 visualizes China's growing investment in its military-industrial base. One area of particular emphasis has been on their shipbuilding industry. As of 2019, China was one of the top three shipbuilding nations by gross ton globally.[M] Their primary military shipbuilding industry China Shipbuilding Industry Corporation, ranked 14th in global defense companies that same year.[M]

Based on the three areas listed above, a nationally focused warfighting concept, military and state-focused academia, and a robust military-industrial complex, China can make future military advances faster than other global competitors. Unsinkable metals will likely be built in China before any other nation for military use because of their military-industrial base and academia's focus within the next five to ten years. It is highly likely that China will use this new metal technique to build the latest version of their unmanned

Figure 94: China's JARI. (Courtesy of South China Morning Post)

surface vessels (USV). Today, China has the JARI the world's first USV with multiple roles – anti-submarine, air defense, and surface combat – and powerful weaponry undergoing its first sea trials.[H] (see figure 94) The incorporation of unsinkable metal to a USV like the JARI will significantly increase its survivability and help to extend sensor coverage further from bases with a low-cost easily produced system. The incorporation of neuromorphic computing would further enhance this system.

Neuromorphic computing is highly likely to be militarized in the next five years by the Chinese. Again, the support of a whole-of-government approach to their future warfare concept allows China to be the best positioned to militarize neuromorphic computing before anyone else. Neuromorphic computing both increases the efficiency of computing and mimics the intelligence of the human mind.[M] When combined with a highly survivable USV, the ability of this USV to run longer and accomplish more with limited human interaction makes it a powerful weapon. When incorporated in the A2AD network, this smarter, more survival system can extend the range of sensing and engaging capabilities, but it can also do it faster with less human interaction. When combined with AI this is highly likely to create a part of the A2AD network that limits US surface and sub-surface fleet access to areas controlled/claimed by China.

China is investing heavily in quantum technology and is likely leading the world in quantum development.[M] They likely are the best poised to develop and deploy an operational quantum radar by 2031.[M] This will provide China a significant advantage in their A2AD network. A quantum radar with its low power signature and the ability to make out fine details of an aircraft through its ultra-high-definition radar picture will have a tactical advantage in any future conflict.[H] Combining quantum radars' ability to negate stealth aircraft movement in China's control airspace with the increased capability of the USV mentioned above significantly increases their A2AD survivability and lethality.

Several western companies like IBM and Microsoft have begun publishing toolkits on using FHE in daily applications.[H] Because these companies are using open-source structuring in their rollout of this tool, it is easily picked up by companies and governments like China. FHE allows research to stay encrypted and still be worked on by powerful cloud-based computing servers.[H] Since the cloud-based servers never decrypt the data, it is near impossible to determine what is being worked on and for whom it is being worked on for. FHE gives China another advantage in using its academic system to solve future technology problems and quickly leapfrog that technology like quantum radars and neuromorphic computing getting it into military planners' hands sooner than other global competitors.[M]

The final piece to China's new A2AD network that will make it impenetrable is the enhanced humans that will run the network. It is likely that by 2035, China will have augmented humans with exocortexes.[L] The combination of human and machine to boost intelligence and memory in humans will make decision-making faster inside the A2AD network.[L] While humans will likely not be controlling every bot on the battlefield, they will continue to receive a vast amount of information on what is occurring. This increase in information will create an environment where AI and human responses will need to be synchronized. An exocortex allows a human to connect to the vast array of machine-stored knowledge and act on it while maintaining all the inputs around them. Exocortexes will greatly increase the human's ability to understand the signals received and apply them to a problem. The increase in intellectual capability that an exocortex provides will likely improve decision-making and reduce friction on the battlefield.


Figure 95: Super Soldier. (Courtesy of Wikipedia)

Despite all of the whole-of-government approach China is putting into their Intelligentized Warfare, they may not be the first to reach these milestones technologies.[M] The US is heavily investing in modernization as laid out in the 2017 National Defense Strategy.[H] One of the US's significant strengths is the partners and allies that they have around the world.[H] Many nations are working to address these five technologies and others that will share their combined intellectual work with the US to counter China. Still, it is highly likely because of the whole-of-government approach and focus on Intelligentized Warfare that China will develop an A2AD network that cannot be penetrated in the next ten years.

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were generally reliable and tended to corroborate one another. There was adequate time, but the analyst worked alone and did not use a structured method. Furthermore, given the estimate's limited time frame, this report is sensitive to change due to new information.

Convergence of Multiple Technologies Likely to Improve Soldier Health Monitoring, Performance Enhancement, and Brain to Computer Interface by 2030

Executive Summary

Four technologies likely to converge include "electric wood" (wood products that conduct electricity or otherwise mimic other products traditionally found in electronics), amorphous metals, medical biodegradable sensors, and microbiome research. The convergence of these technologies is likely to improve Soldier performance through health monitoring, performance enhancement and brain to computer interface by 2030, despite the ethical, legal, and social implication concerns. Other military disciplines likely to be influenced by these technologies include improved medical capabilities, military equipment, and communication networks. China has a high interest in amorphous metals, biodegradable sensors, and electric wood, as shown through the number of research papers, patents and industry partners involved.

Discussion

The most exciting technology with the highest level of convergence factors is "electric wood." It is likely to influence the fields of communication, sensors, and computing. Biodegradable and renewable in nature, CNC are derived from cellulose fibers.[H] CNCs provide low cost, eco-friendly, sustainable materials which can be used for various applications such as electronics/sensors, biomedical and energy.[H] In 2020, a New Zealand based team created a wood based flexible circuit with strong mechanical properties, stronger than most engineering materials, and could be used in sensors, smart packaging and wearable devices.[H] (see figure 96) The application of a flexible circuit will likely impact an array of items such as wearable devices, drones and communication networks.[H] Possible Department of Defense use of biodegradable electronics with incorporated wood cellulose products, include drones and robotics with planned end of life timelines.[M] Another utility includes deploying electronics with heat-triggered self-destructing capability to increase the devices security.[H]

Figure 96: Flexible, wearable electronics monitor vital signs, monitor and interface with the human body. (Courtesy of IEEE)

Amorphous metal, non-crystalline metal with glass-like structure, is likely to influence the fields of communication, sensors, and computing. Research into amorphous metals continues to advance the possibilities of potential applications fields, new compositions of metallic alloys, and novel processing routes.[H] Potential application fields include

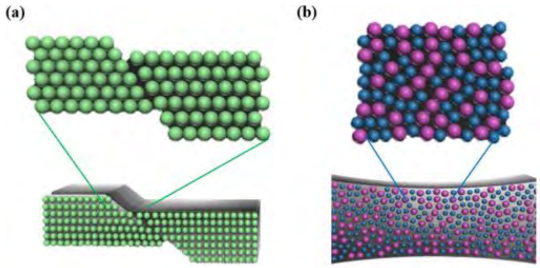

Figure 97: Comparison of crystalline (left) vs. amorphous material (right) which shows how the amorphous material bends and does not break. (Courtesy of Nature.com)

structural materials, hydrogen storage materials, soft magnetic materials and biomaterials.[H] Amorphous metals will likely be used in medical instruments, military vehicles and aerospace industries.[H] In 2019, Jung et al., researchers from various University's in the Republic of Korea, published a study on the use of amorphous metals for a multi-functional sensor in electronic skin (e-skin). This skin tracks pressure, temperature, has an optical sensor and a microheater for injecting medicine which makes it useful in applications such as human-machine interactive interfaces, healthcare-monitoring systems, and medical diagnostic devices.[H] (see figure 97) Amorphous metals can provide a break-proof, lighter casing and EMI shielding properties.[H] EMI shielding in electronics can protect from a disruption of signals and extremely important capability in the military community.[H] Amorphous metals can also be used in the production of drones due to its unique properties.[H]

Medical biodegradable sensors are likely to influence the fields of sensors and communication. In August 2020, respected tech-forecasting firm Gartner identified Biodegradable Sensors in its 2020 Hype Cycle for Emerging Technologies, as one of five emerging trends for the next ten years.[H] A research team from Stanford University developed an implantable, biodegradable sensor for medical monitoring which measures strain and pressure, as part of a larger project researching biodegradable electronics.[H] Advancement in sensor research includes multiple clinical research teams working to develop biodegradable sensors which can be placed within the body.[H] Though initially designed for medical use, the development of body-integrated, biodegradable sensors would allow individual Soldier status information, detection of stress overload on physiological and physical systems, enhancing Soldier performance.

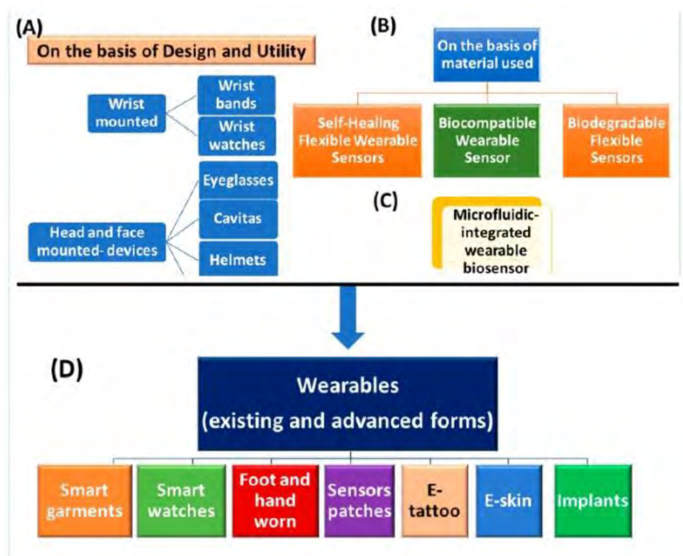

Figure 98: Evolution of sensors. (Courtesy of Molecules Research Paper)

Microbiome research advancement is likely to influence sensors and communication as an enabling element within the body. Research in 2020 identified how intestinal bacteria can affect the CNS by communicating in a bidirectional network with signaling pathways called the gut-brain axis.[H] The understanding of the intestinal microbiome is likely to strengthen future disease prevention strategies, personalized healthcare regimens and novel therapeutic interventions.[M] The microbiome interacts with over 70% of the immune system, turning genes on and off, and the circadian rhythm.[H] Microbiome research will likely lead to an enhancement of Soldier performance through optimizing the bodies network, improving the interaction with sensors (improvement of Brain-Computer Interface) and improving performance through probiotic augmentation.

Figure 99: Microbiome research. (Courtesy of Lawson Health Research) To view click on the photo.

One likely convergence of electric wood, amorphous materials, medical biodegradable sensors, and tribo-electric nanogenerators is e-skin, which improves the opportunity to

Figure 100: Understanding electronic skin fabrication and uses. (Courtesy of Wiley Online Library)

create an augmented, monitored, enhanced performance Soldier. Skin is the largest organ in the human body, holding multiple properties such as tactile sensing capability, stretchability, self-healing, and high mechanical toughness.[H] Devices which mimic these properties are called electronic skin or e-skin.[H] E-skin applications include skin attachable devices and robotics. E-skin requirements include stretchability, flexibility, biocompatible materials, tactile sensing, self-healing, wireless capability, multifunctioning sensors (vital signs, biofluids), neuromorphic devices, neural interfaces, and aesthetically suitable.[H] In June 2020, a science research team from China designed a flexible, stretchable, breathable, biodegradable, and antibacterial e-skin, that included tribo-electric nanogenerators, which allowed for effective mechanical energy harvesting and whole-body physiological signal monitoring.[H]

Figure 101: Chinese interest in building "biologically enhanced" Soldiers developing faster than the US. (Courtesy of Frederic J. Brown/Getty Images)

Chinese interest in amorphous metals, biodegradable sensors and electric wood shows through the number of research papers, patents and industry partners involved. In 2018, Chih-Yuan Chen published a peer reviewed paper in which he analyzed patent bibliometric information on BMGs in order to forecast the development trajectory as being in the growth stage from 2000-2015.[H] His research showed the highest number of patents originated in China from commercial businesses or research institutions.[H] Shenzhen Amorphous Technology Co. Ltd. in China, creates amorphous ribbons which can be shaped into quieter, more energy efficient products used in 5G, transportation, and national defense security.[H] Another Chinese company, WENERGY, provides amorphous metal products such as transformer cores and electromagnetic interference shielding materials for electronic devices to the military industry.[H] Chinese backed researchers recognized wood cellulose could be used as a versatile polymer in biodegradable electronics as a functional component such as advanced light management layer, high capacitance conductor, or as a smart material such as a humidity sensor, adaptable adhesive or piezoelectric component.[H] Two different Chinese research groups published papers in 2020 describing research into biodegradable sensors. One group researched body-integrated, biodegradable sensors for health monitoring and in situ treatment.[H] The second group's research involved creating a biocompatible and biodegradable polysaccharide-based flexible humidity sensor which could monitor human respiration.[H] China is reportedly developing "biologically enhanced" Soldiers, which is also an interest of the US Army. An article on this subject states "Given China's speed in advancing CRISPR research, the possibility that the country is exploring the use of gene editing on soldiers isn't far-fetched."[M]

Ethical concerns impact performance enhancement research and testing, which includes the use of probiotics, drugs, implantable devices, or brain-computer interface within the human body. Within microbiome research alone, there are multiple ethical, legal, and social implications, which include informed consent, data sharing, privacy protection, public perception of research, use of research data, and the alteration of people's conception of health and disease and what it means to be "human".[H] Despite the ethical concerns, researchers will continue to advance the field due to the tremendous worthwhile uses behind the science. The Human Biome Project allocated a portion of their budget to studies into the ethical, legal, and social implications of microbiome research.[H] The military recognized the issue concerning "the whole supersoldier business", and funded a project to investigate Soldiers' participation in experiments which augment a person's natural abilities.[H]

Analytic Confidence

The analytic confidence for this estimate is *High*. Sources were generally reliable and tended to corroborate one another. There was adequate time, but the analyst worked alone and did not use a structured method. Furthermore, given the lengthy time frame of the estimate, this report is sensitive to change due to new information.

CONCEPT SQUAD

Annexes

Annex A

Terms of Reference:
Tomorrow's Technological Blitzkrieg

For:

Mr. Harry "Ed" Mornston, Director, Intelligence and Security
Army Futures Command

By:

Concept Squad
U.S. Army War College

November 13, 2020

Terms of Reference:

Tomorrow's Technological Blitzkrieg

Requirement:

What "exciting technologies"[1] will likely converge[2] in militarily relevant ways between 2030 and 2040 to challenge U.S. interests at home and abroad?

Methodology:

The team will consider multiple models to develop the problem's details and decide upon the best approach as we advance the research.

- The team will begin their research by identifying likely "exciting" technologies in various research and development stages. Once identified, the team will likely integrate the findings of these "exciting" technologies to reveal potential points of convergence in a militarily relevant way.

- The team will consider but will not be limited to the following analytic tools or methodologies:
  - *One-on-One Interviews*. Interviews will likely provide an opportunity to discover what technologies industry, academia, and venture capitalists are investing money into for use in the next decade.
  - *Comparative Case Study Research*. Comparative Case Study Research will likely allow the team to deep dive into a thorough understanding of available and relevant data.
  - *Multi-Criteria Decision Analysis (MCDA)*. Multi-Criteria Decision Analysis will likely assist the team in breaking the question down into subcomponents, analyzing each part separately, and then assembling them for a decision.
  - *Social Network Analysis*. Social Network Analysis will possibly help the team determine where a convergence of technologies will occur.

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[1] **"Exciting"** technology incorporates developing, emerging, and surprising technologies in one term. **Developing**-Technologies undergoing growth or evolving, which are part of current science and technology initiatives such as robotics, Artificial Intelligence (A.I.), Autonomous Systems (AS), and synthetic biology. **Emerging**- Technologies whose coming into being is not-yet fully understood or researched and have unfulfilled but promising potential. **Surprising-** Technology with a disparity between public and private financial investment and the amount of public interest it generates.

[2] **Converge**-The process of seemingly unrelated technologies connecting, forming an unexpected and complementary military capability.

- *Complex Event Analysis*. Complex Event Analysis will likely allow the team to aggregate and analyze event data from multiple sources, identify cause-and-effect relationships, and understand real-time or near-term intentions.

- The team will consider using, but will not be limited to, the following tools to support the above analytic tools and methodologies:
  - *Mindmeister*. Mindmeister will likely enable mind-mapping and large format printing to link broad concepts and different domains over large timeframes, allowing for data visualization and the detailed inspection of initial results.
  - *TinkerCad (3D Design), Makerbot Z 18 (3D Printing), and Oculus Quest (V.R.)*. TinkerCad, Makerbot Z 18, and Oculus Quest will facilitate the 3D visualization of data and results, affording situational exercises' realistic viewpoints and reducing the cost to run these cause and effect studies.
  - *Fivver (Gig Economy) and Alexa (Digital Assistant)*. Fivver and Alexa will allow the team to acquire expert and speedy assistance in precision tasks.
  - *Feedly*. Feedly will provide the team will rapid collection management and aggregation of information.
  - *Zotero*. Zotero will allow the team to efficiently manage the storage and flow of research information and products.

- The team will consider breaking down the term into the following timeline:
  - The team will conduct research continuously throughout the project with the aggregation of information from industry, academia, and venture capitalists. The team will consider a site visit to the Institute of Creative Technologies (ICT) and other like institutions to understand better how academia directs its principal customers' resources.
  - Upon agreement of the Terms of Reference, the team will study and identify "exciting" technologies that will likely be pervasive enough for use by threats in the next two decades. We will then explore how these technologies might converge to create exponential consequences and determine where U.S. interests may be challenged at home and abroad.
  - The team will aggregate each unique area of the question against each other and fuse the findings into a final report.

Challenges:

The team may face challenges due to being current U.S. Army War College students with competing requirements. The team will be learning to become futurists while completing the project. Additional challenges may include:

- *Time.* The team must complete the project by April 2021. We are taking this course in addition to the USAWC core curriculum.

- *COVID*-19. Current environmental conditions and travel restrictions could limit firsthand sources' availability and restrict travel to explore developing technologies.

- *Money.* Money is available for travel and other expenses, but there are limitations.

- *Proprietary Information.* Industry, Academia, and Venture Capitalists value their intellectual property and details associated with their Research & Development, contributing to a level of secrecy that may prohibit full disclosure of information they possess.

- *Limited information sources.* The team has access to mostly open-source information, and the final product will be unclassified.

- *Data and technology.* The team will need to learn how to utilize current technology and methodologies to analyze the extensive data collected.

- *Classroom environment.* The team is executing the study in the context of a class at the USAWC.

Resources:

The main challenge described in the previous section, U.S. Army War College students completing this project, can also be construed as a resource. Each exhibited the knowledge, skills, and abilities necessary to be selected as a resident attendee.

- *Personnel.* Each team member has served in the defense industry at varying and complementary levels over the last 20+ years. All have exposure to the vast array of conventional, unconventional, near-peer, and asymmetric threats that currently exist. Most of the team has experience analyzing a problem set either in an academic environment or a realistic environment where the results were necessary to progress toward a decision. Most of the team has an advanced degree, which required detailed research into a unique problem set.
    - Three have served as battalion commanders and bring leadership and change management skills.
    - Two have experience on general officer staffs and briefing senior general officers or members of the Senate. They bring organizational skills to the team. They have connections across the DA and DAF civilian and military networks.

- *Institutional Resources and Databases.* The team has access to a variety of institutional resources, including:
    - Army Heritage Education Center
        - An institution well versed in research topics, techniques, and analysis regarding government and military areas of study.
    - U.S. Army War College Library Online Databases:
        - Journals
        - Ebscohost
        - JSTOR
        - USAWC Futures Library Guide

Administration:

The team will complete the final product no later than April 30, 2021.

- The team will be available to present key findings to Mr. Ed Mornston (AFC DOIS) O/A 26-30 April 2021.

- The team will complete a final report detailing the complete findings in a PDF version for easy dissemination.

- Correspondence with Army Futures Command will occur through the primary points of contact, Mr. Keith Hamlin or Mr. Mike Dennis.

- Team members include:
  - COL Johnny Casiano, John.Casiano@armywarcollege.edu (Primary)
  - Ms. Jo Dempsey (DA Civ.), JoAnne.Dempsey@armywarcollege.edu (Alternate)
  - Mr. Gregory Lynch (A.F. Civ.), Gregory.Lynch@armywarcollege.edu
  - LTC Andy Pannier, Andy.Pannier@armywarcollege.edu
  - LTC Bill Snook, William.Snook@armywarcollege.edu

Annex B
Assessing Analytic Confidence

The analysts that wrote this report is a non-subject matter experts. They worked individually and collaboratively to answer the questions. They utilized a combination of structured analytic techniques including nominal group technique and network analysis among others. The team evaluated their analytic confidence utilizing Peterson's Analytic Confidence Factors coupled with the Friedman Corollaries.

Peterson Factors

- How reliable are the sources?
- How well do the independent sources corroborate each other?
- What is my/my team's level of expertise?
- How effective was my analytic collaboration?
- Did I use any structured techniques in my analysis?
- How difficult did I perceive the task to be?
- Did I have enough time to complete the task?

Friedman Corollaries

- Is my estimate within the range of reasonable opinion surrounding the question?
- How likely is it that new information will change my estimate?

Peterson's Analytic Confidence Worksheet

	Points Possible	Points
Use of Structured Method(s) In Analysis	**(1-10)**	
For example: ACH, IPB, Social Networking, Bayes, Simulation, etc…		
10 indicating highest possible score when considering factors below		
Consider		
Number of		
Applicability of methods to the analysis		
Level of robustness of method		
Degree to which methods' results coincide		
Overall Source Reliability	**(1-10)**	
A rating of 10 indicates the highest reliability		
Source Corroboration/Agreement: *Level of conflict amongst sources*	**(1-5)**	
5: No confliction amongst sources		
4: Very little conflict amongst sources		
3: Moderate conflict amongst sources		
2: Significant conflict amongst sources		
1: Sources conflict on nearly all points		
Level of Expertise on Subject/Topic & Experience	**(1-5)**	
5: Deep intimate knowledge and understanding & 3+ years experience with topic		
4: Wide knowledge & 1-3 years experience with topic		
3: Moderate knowledge & 6-12 months experience with topic		
2: Minimal knowledge & 0-5 months experience with topic		
1: No knowledge & no experience with the topic		
Amount of Collaboration:	**(1-5)**	
5: Part of aggregated individual analyses		
4: Work on a team		
3: Worked with a partner		
2: Casual discussion		
1: Completely individual work		
Task Complexity	**(1-5)**	
5: Minimally complex & challenging		
4: Somewhat complex & challenging		
3: Moderately complex & challenging		
2: Quite complex & challenging		
1: Very complex & high challenging		
Time Pressure: *Time given to make analysis*	**(1-5)**	
5: No deadline		
4: Easy to meet deadline		
3: Moderate deadline		
2: Demanding deadline		
1: Grossly inadequate deadline		
	Score:	
	Total Possible:	**45**
	Score/Total Poss:	
		X10
	Analytic Confidence Adjusted Score:	

Annex C

Standard Primary Source Credibility Scale

Source reliability is noted at the end of each citation as low L, moderate M, or high H. The citation is hyperlinked to the source, unless the source is a paid subscription; in that instance a footnote is provided at the end of each writing illustrating the source for credibility. Source reliability is determined using the Trust Scale and Website Evaluation Worksheet found in Annex

Importance	Factor	Description	Satisfies Criteria (Yes /No)
HIGH	Has a good track record	Source has consistently provided true and correct information in the past	
	Information can be corroborated with other sources	Information provided by the source corroborates with information from other primary and/or secondary sources	
	Information provided is plausible	High probability of the information being true based on the analyst's experience of the topic/subject being investigated	
	Information is consistent and logically sound	Information provided is consistent when queried from different angles and is logically sound	
	Perceived expertise on the subject	Source is perceived to be an expert on the subject / topic being investigated and/or is in a role where subject knowledge is likely to be high	
	Proximity to the information	Source is close to the information – a direct participant or a witness to the event being investigated	
	Perceived trustworthiness	Source is perceived to be truthful and having integrity	
MEDIUM	No perceived bias or vested interest in the subject / topic being investigated or on the outcome of the research	Source has no perceived bias or vested interest in the subject / topic being investigated or on the outcome of the research	
	Provides complete, specific and detailed information	Information provided is specific, detailed and not generic	
LOW	Is articulate, coherent and has a positive body language	Source is articulate, coherent, has a positive body language and does not display nervousness or body language that can be construed to be evocative of deceptive behavior	
	Recommended by another trusted / credible third party	Source is recommended by others the analyst trusts but the analyst herself does not have any direct experience working with the source	
	Sociable	Source comes across as outgoing and friendly. Easy to get along with and talk to	
	Perceived goodwill to the receiver	Perceived intent or desire to help the receiver or the analyst	

Annex D

Trust Scale and Web Site Evaluation Worksheet

Trust Scale and Web Site Evaluation Worksheet
(Updated OCT 2013)

Piece of Evidence #:												Score:	Trust Scale:
Criteria	**Tips**	**Value**	Y or N	Y or N	Y or N	Y or N	Y or N	Y or N	Y or N	Y or N	Y or N	0	15-20 High
Content can be corroborated?	Check some of the site's facts	2											11-15 Moderate
Recommended by subject matter expert?	Doctor, biologist, country expert	2											6-10 Low
Author is reputable?	Google for opinions; ask others	2											5-0 Not Credible
You perceive site as accurate?	Check with other sources; check affiliations	1.5											
Information was reviewed by an editor or peers?	Science journals, newspapers	1.5											
Author is associated with a reputable org?	Google for opinions; ask others	1.5											
Publisher is reputable?	Google for opinions; ask others	1.5											
Authors and sources identified?	Trustworthy sources want to be known	1											
You perceive site as current?	Last update?	1											
Several other Web sites link to this one?	Sites only link to other sites they trust	1											
Recommended by a generalist?	Librarian, researcher	1											
Recommended by an independent subject guide?	A travel journal may suggest sites	1											
Domain includes a trademark name?	Trademark owners protect their marks	1											
Site's bias in clear?	Bias is OK if not hidden	1											
Site has professional look?	It should look like someone cares	1											
Total		**20**											

19 Dec 2001: The criteria and weighted values are based on a survey input from 56 analysts. For details see: http://daxnorman.googlepages.com/analysis. Edited for simplicity by Kristan J. Wheaton, OCT 2013
3 Feb 2012: Excel Spreadsheet which adds auto-sum was produced by Bill Welch, Deputy Director, Center for Intelligence Research Analysis and Training, Mercyhurst College
26 Jan 2013: Trust Scale and Web Site Evaluation Worksheet is in the PUBLIC DOMAIN.

Annex E

Kesselman List of Estimative Words

Certainty 100%

Almost Certain	86-99%
Highly Likely	71-85%
Likely	56-70%
Chances a Little Better [or Less]	46-55%
Unlikely	31-45%
Highly Unlikely	16-30%
Remote	1-15%

Likelihood

Impossibility 0%

Annex F
Acronyms

1D – 1 Dimension
3D – 3 Dimensions
4D – 4 Dimensions
5D – 5 Dimensions
5G – Fifth-generation Wireless
6G – Sixth-generation Wireless
A2AD - Anti-Access/Area Denial
AC – Alternating Current
AI – Artificial Intelligence
AMMS – Academy of Military Medical Sciences
ARL – Army Research Lab
BCI – Brain-Computer Interface
BtBI – Brain to Brain Interface
BMG – Bulk Metallic Glasses
BMI – Brain Machine Interface
CETC – Chinese Electronics Technology Group Corporation
CIIF – China International Industry Fair
CMOS – Conventional Metal Oxide Semiconductor
CNC – Cellulose Nanocrystals
CNS – Central Nervous System
CNTT – Carbon Nanotube Transistor
CNT – Carbon Nanotube
COVID – Coronavirus Disease
COVID 19 – Coronavirus Disease 2019
CPU – Central Process Unit
CVD – Chemical Vapor Deposition
DARPA – Defense Advanced Research Projects Agency
DA – Department of the Army
DAF – Department of the Air Force
DC – Direct Current
DCM – Digital Coding Metamaterial
DNA – Deoxyribonucleic Acid
EMG – Electromagnetic Generators
EMI – Electromagnetic Interference
EU – European Union
FDA – Food and Drug Administration
FHE – Fully Homomorphic Encryption

FMT - Fecal Microbiota Transplants
FUS – Focused Ultrasound
Gbps – Gigabits per second
GHz – Gigahertz
HELMI – High-End Laboratory for Military Intelligence
HF – High Frequency
ICT – Institute of Creative Technologies
IoB – Internet of the Body
IoBNT – Internet of Bio-nano Things
IoS – Internet of Senses
IR – Infrared Technology
LASIK – Laser-Assisted In Situ Keratomileusis
LED – Light Emitting Diode
LiFi – Light Fidelity
LOS – Line of Sight
LWE – Learning With Errors
MCIM – Multi-Criteria Intelligence Matrices
MDSS – Multi-Domain Sensor Systems
MIT – Massachusetts Institute of Technology
ML – Machine Learning
MOST – Ministry of Science and Technology
MRSA – Methicillin-resistant Staphylococcus Aureus
MWCNT - Multi-wall Carbon Nanotubes
NASA – National Aeronautics and Space Administration
OE – Operating Environment
OTD – Optical Trap Display
PED – Process, Exploit, Disseminate
PHE – Partially Homomorphic Encryption
PRC – People’s Republic of China
R&D – Research and Development
RDT&E – Research, Development, Testing, and Evaluation
RLWE – Ring-Learning With Errors
RWTH – Rheinisch-Westfälische Technische Hochschule
SH – Superhydrophobic
SHE – Somewhat Homomorphic Encryption
SWCNT - Single-wall CarbonNnanotubes
Tbps – Terabits per second
TENG – Triboelectric Nanogenerator
TFT – Thin Flexible Transistors
THz - Terahertz

USAWC – United States Army War College
USV – Unmanned Surface Vessel
UV - Ultraviolet
VLC – Visible Light Communications
WEP – Words of Estimative Probability
WiFi – Wireless Fidelity

Annex G
Briefing Slides

The Convergence of "Exciting" Technology Between 2030 -2040

COL Johnny Casiano, Mrs. Jo Dempsey, Mr. Gregory Lynch, LTC Andy Pannier,
COL William Snook

Words of Estimative Probability

Kesselman List of Estimative Words

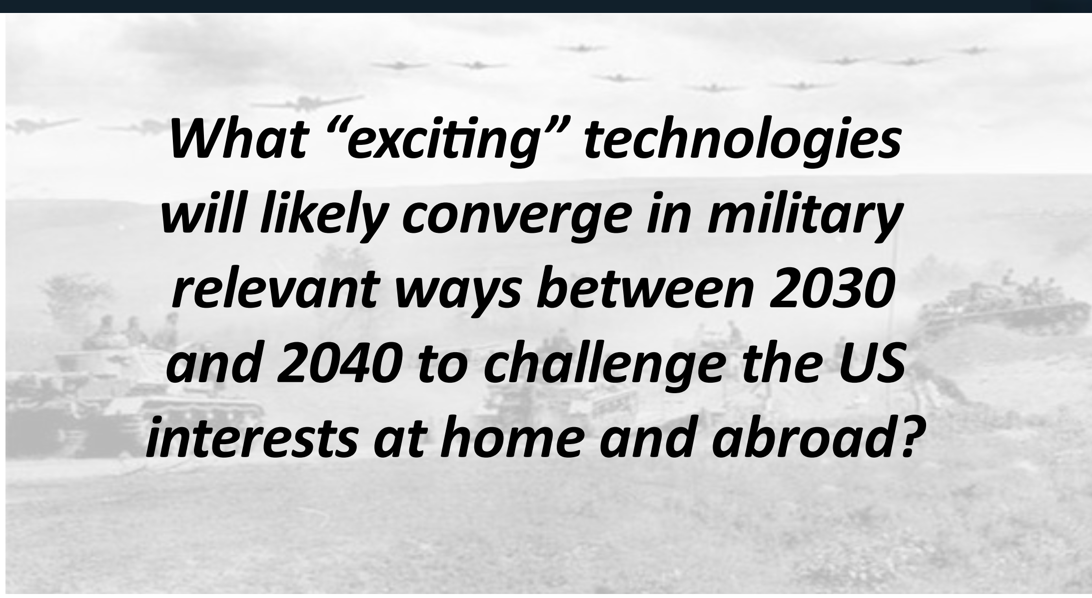
Certainty 100%	
Almost Certain	86-99%
Highly Likely	71-85%
Likely	56-70%
Chances a Little Better [or Less]	46-55%
Unlikely	31-45%
Highly Unlikely	16-30%
Remote	1-15%
Impossibility 0%	

Likelihood

Analytical Confidence

LOW **MODERATE** HIGH

Question



“Exciting” Technology

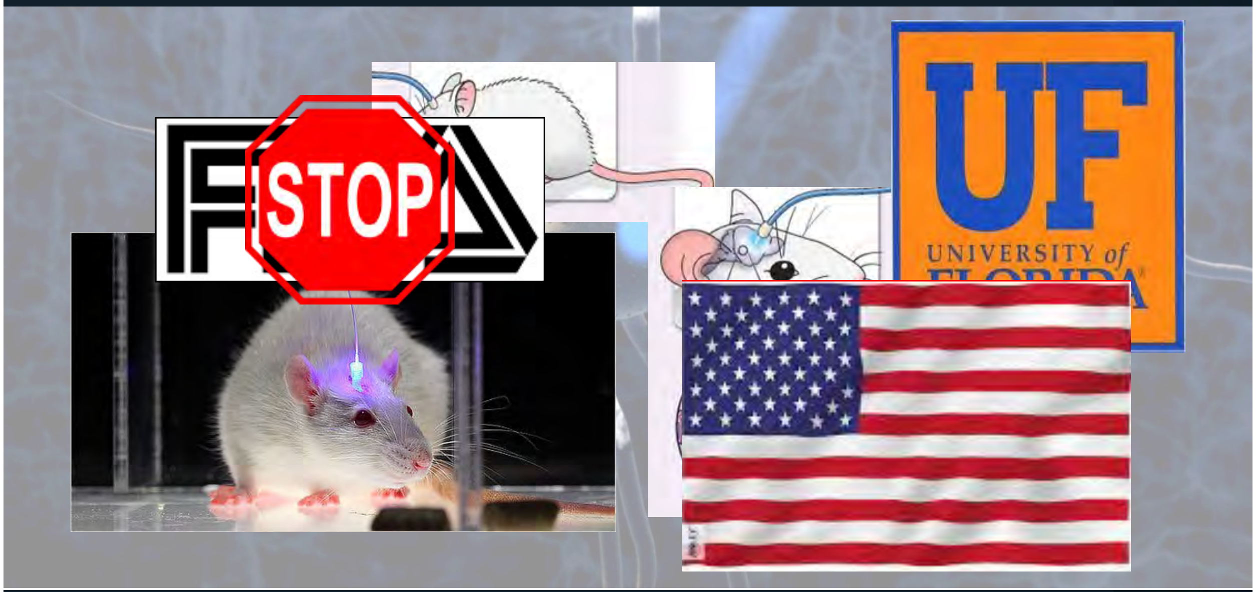
Optogenetics
Triboelectric Nanogenerators
Bio-Nano Processors
Amorphous Metals
Neural Lace
Parallel Reality
Light Bending Metamaterials
Superhydrophobic Materials
Digital Telepathy
Exocortex
4-D Printing
Data Storage Glass
Electric Wood
Photophoretic Trap Volumetric Display
Fully Homomorphic Encryption
Microbiome
Carbon Nanotube Transistors

171 Technologies

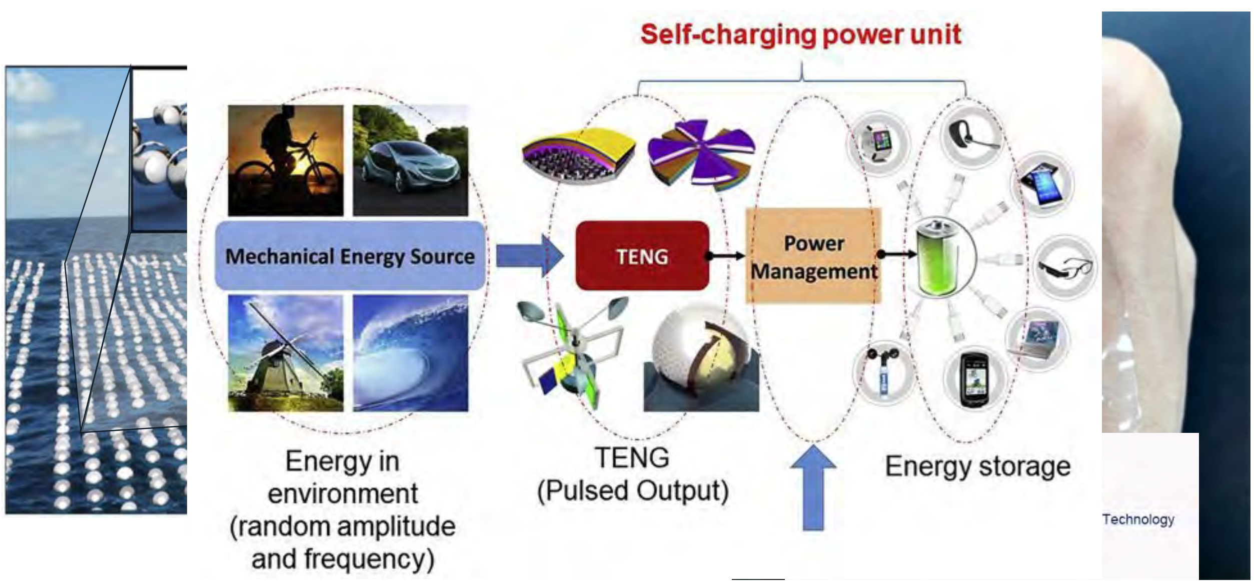
17 “Exciting” Technologies

Optogenetics

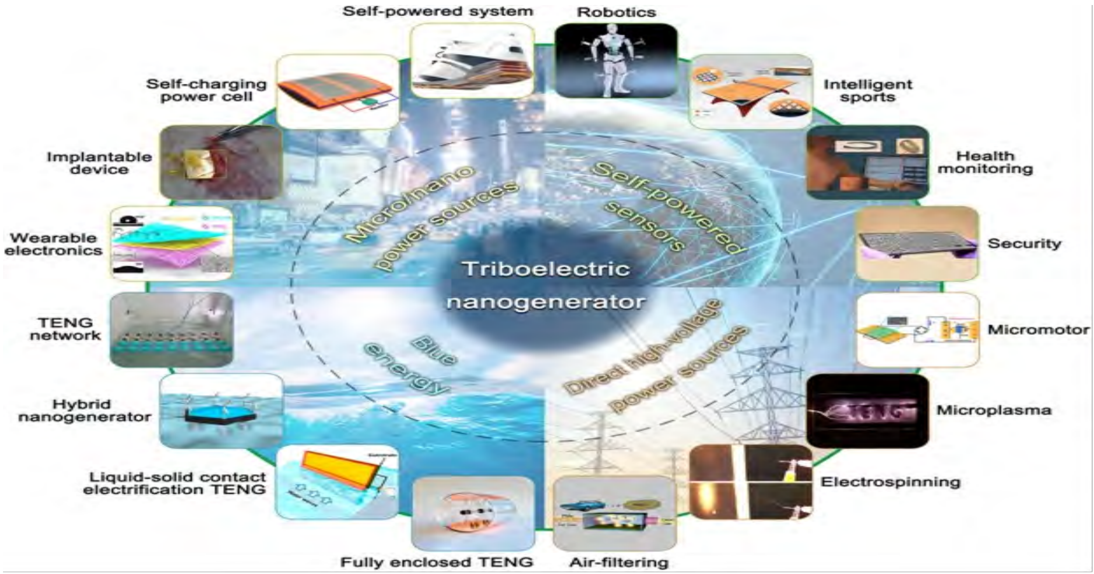
Optogenetics



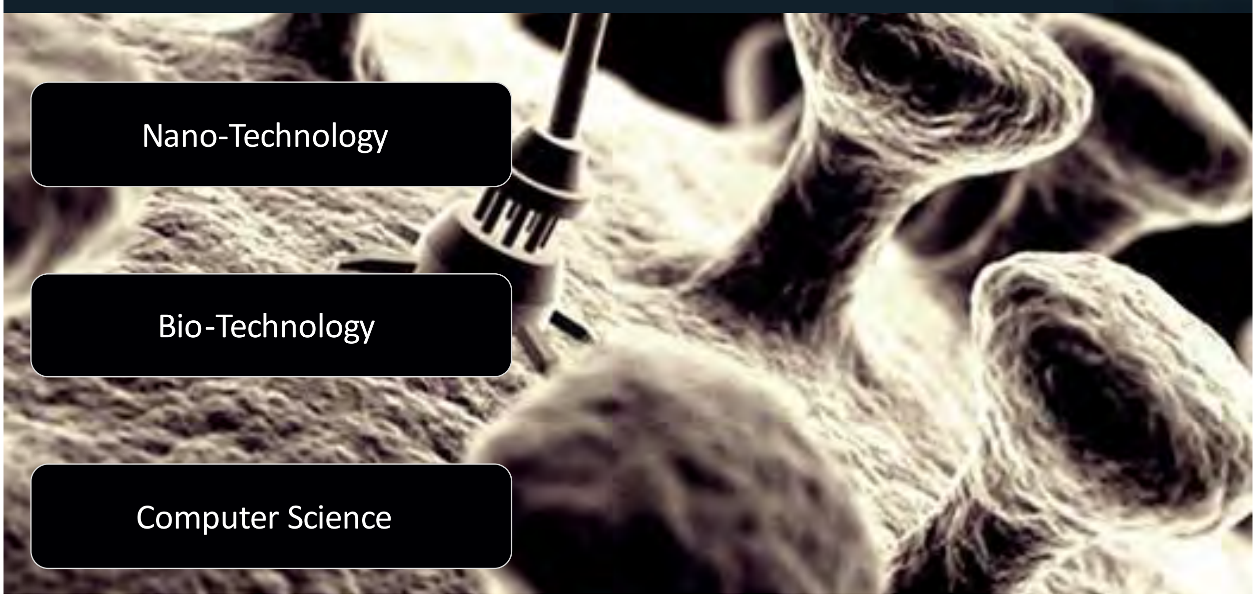
Triboelectric Nanogenerators



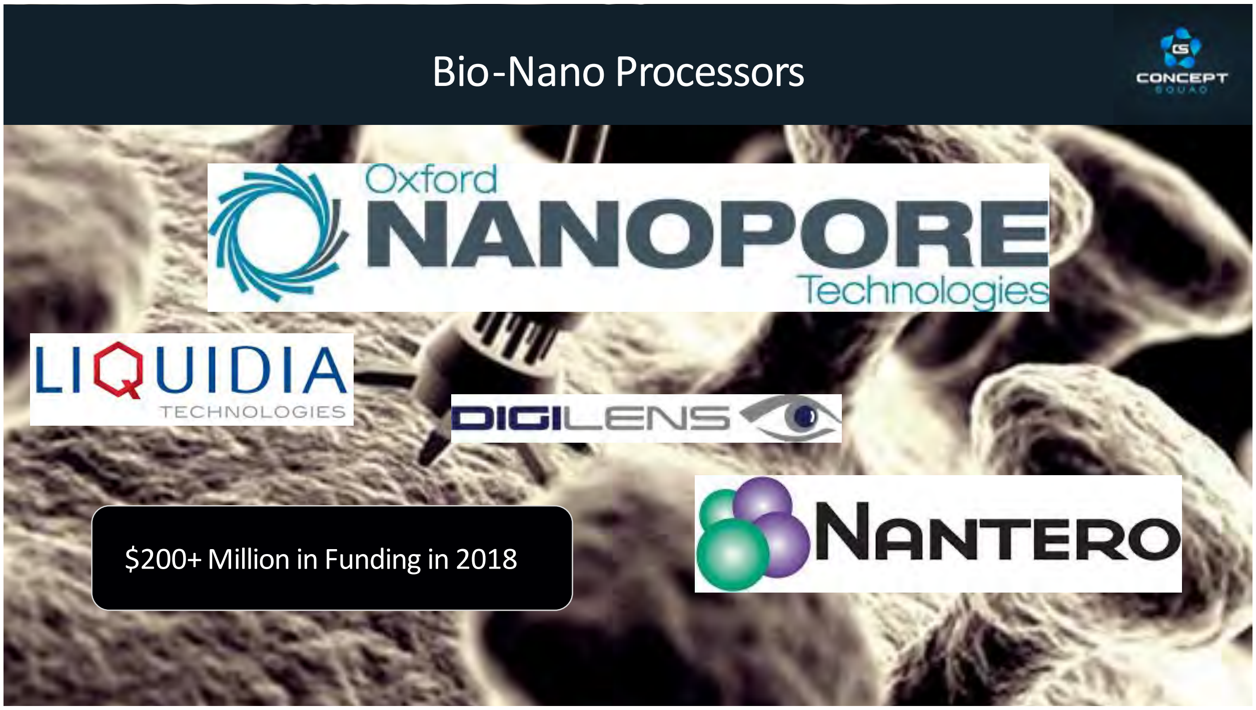
Triboelectric Nanogenerators



Bio-Nano Processors



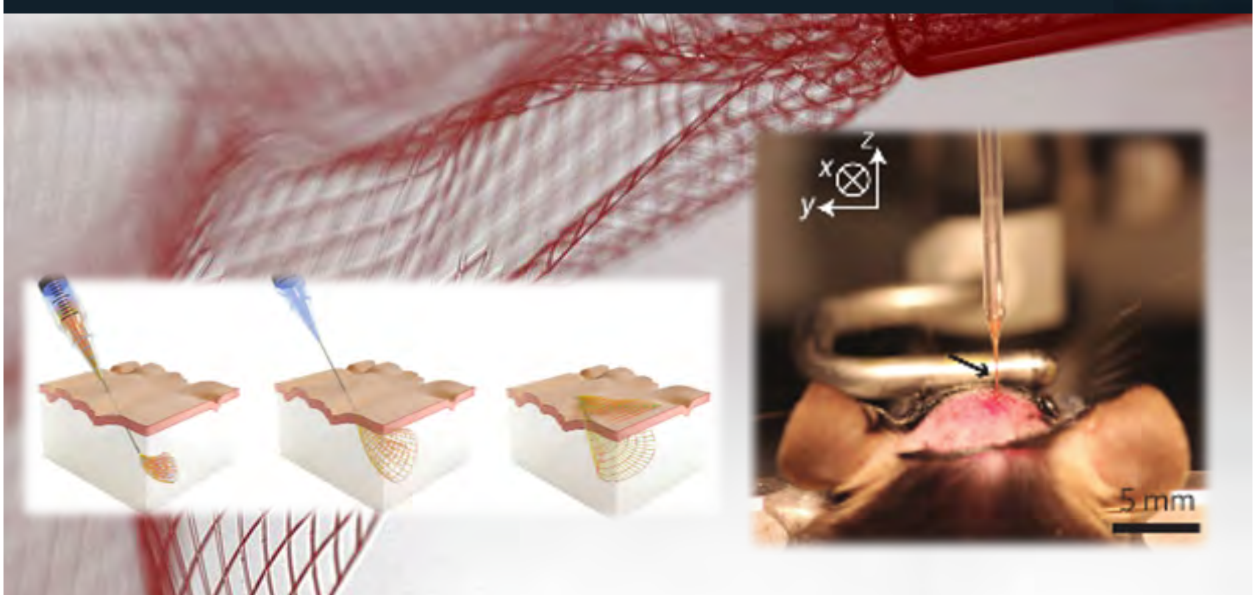
- Nano-Technology
- Bio-Technology
- Computer Science


Bio-Nano Processors
CONCEPT SQUAD
Oxford NANOPORE Technologies
LIQUIDIA TECHNOLOGIES
DIGILENS
NANTERO
$200+ Million in Funding in 2018

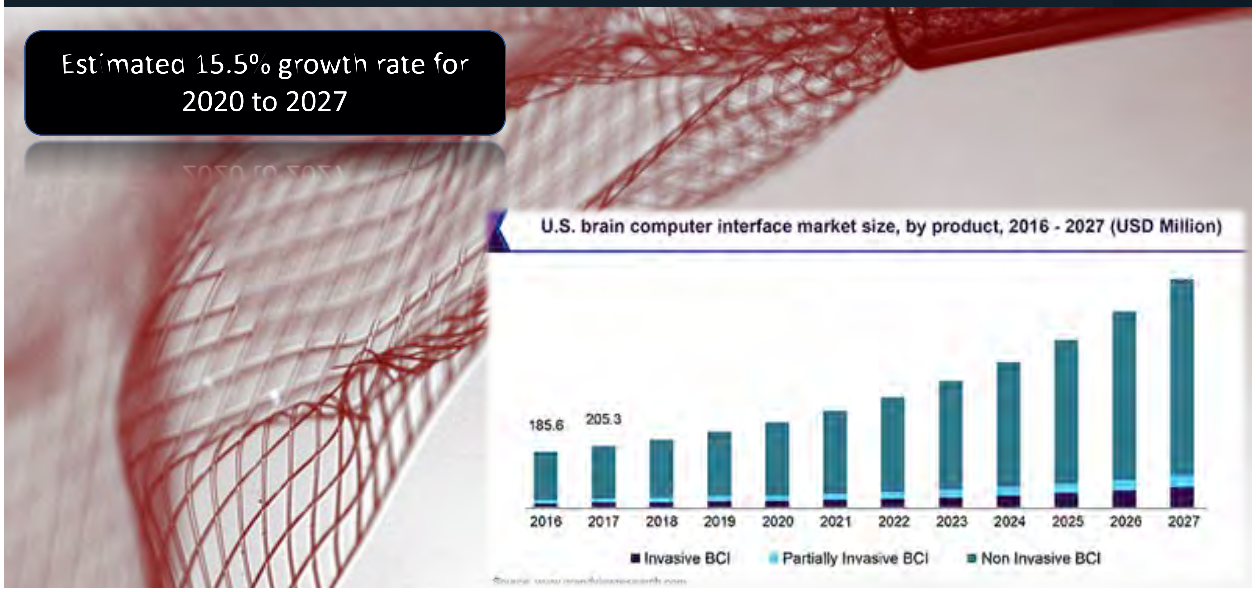

Amorphous Metals
CONCEPT SQUAD
Metal Structure
Amorphous Structure
(schematic illustration)
Steel
Amorphous Metal

Amorphous Metals

Neural Lace

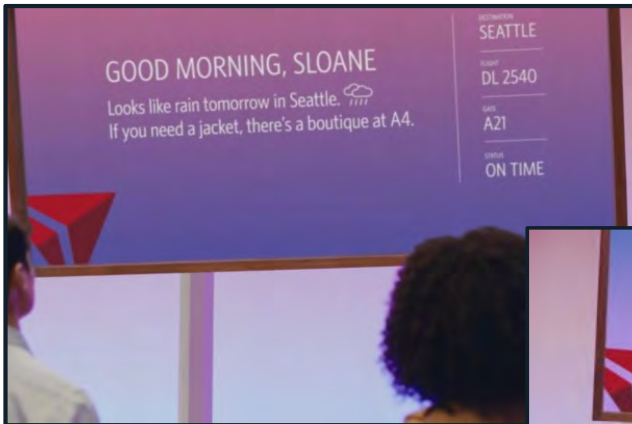


Neural Lace

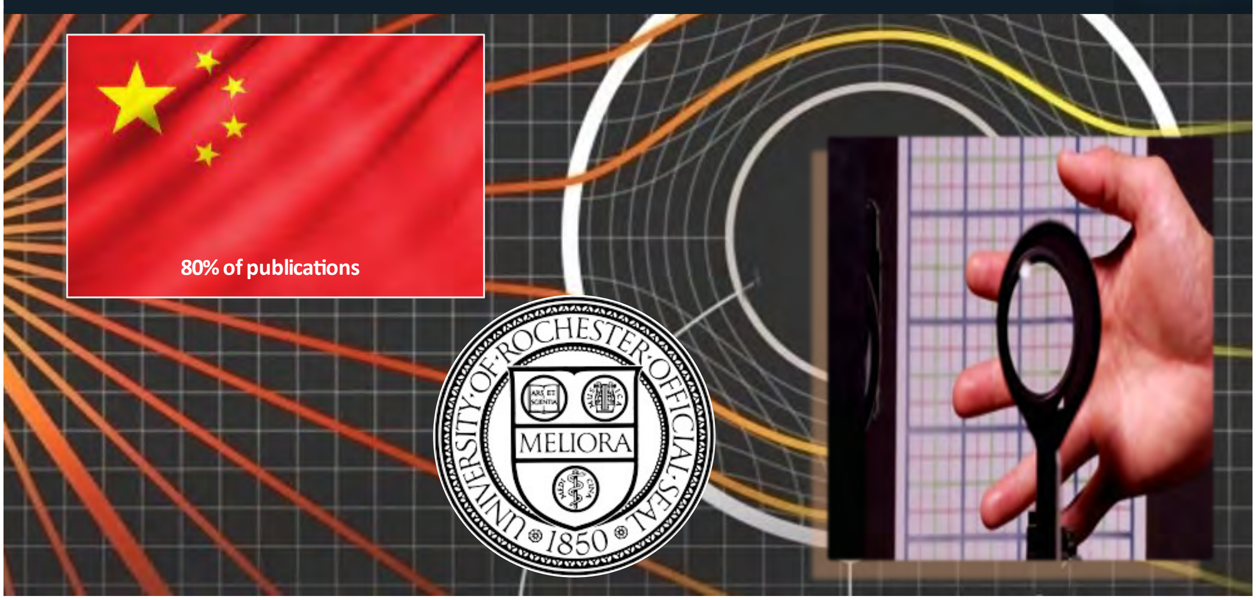


Parallel Reality

Parallel Reality



Light Bending Metamaterials



Superhydrophobic Materials

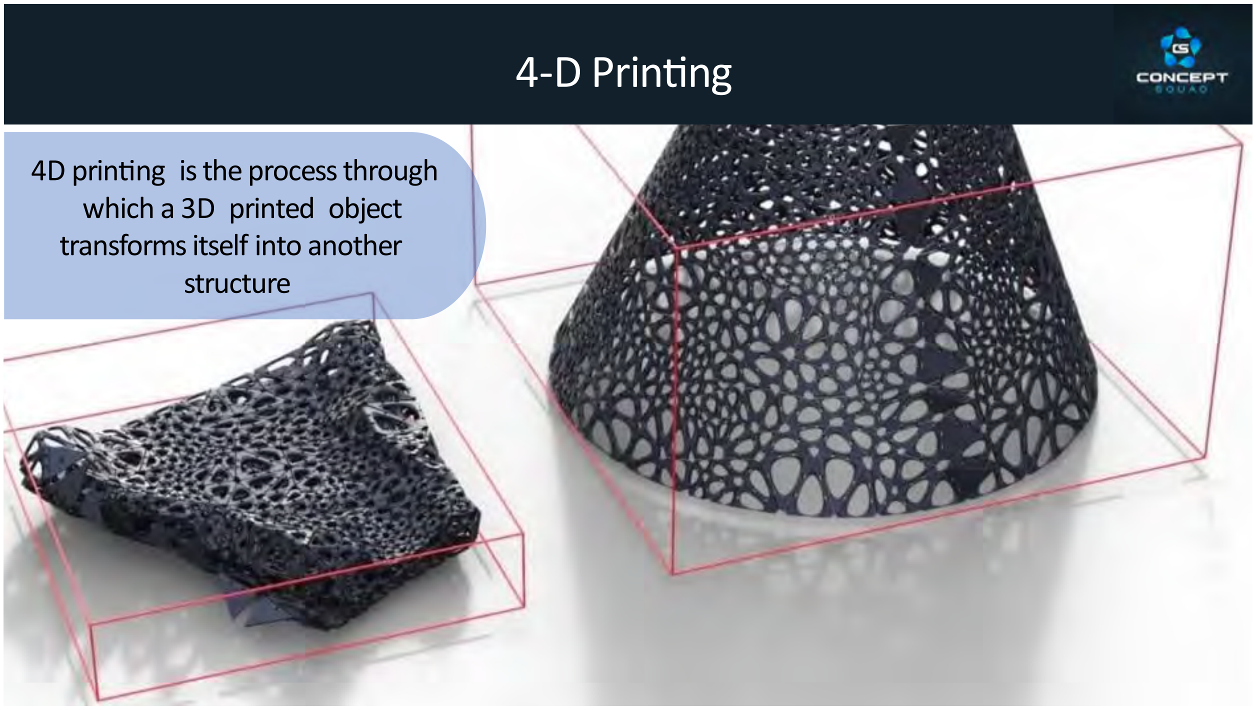
Puncturing the material and it *still* wouldn't sink

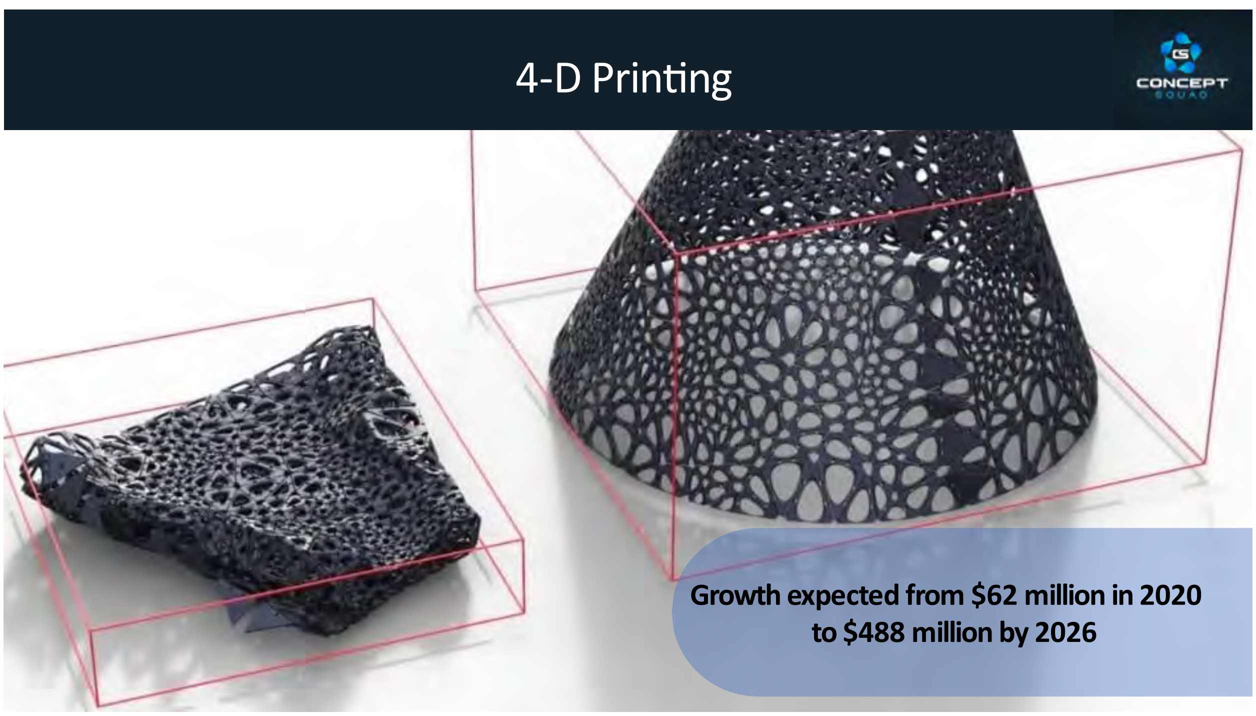
Even after being forced to submerge underwater for months the design was able to float back to the surface

Superhydrophobic Materials

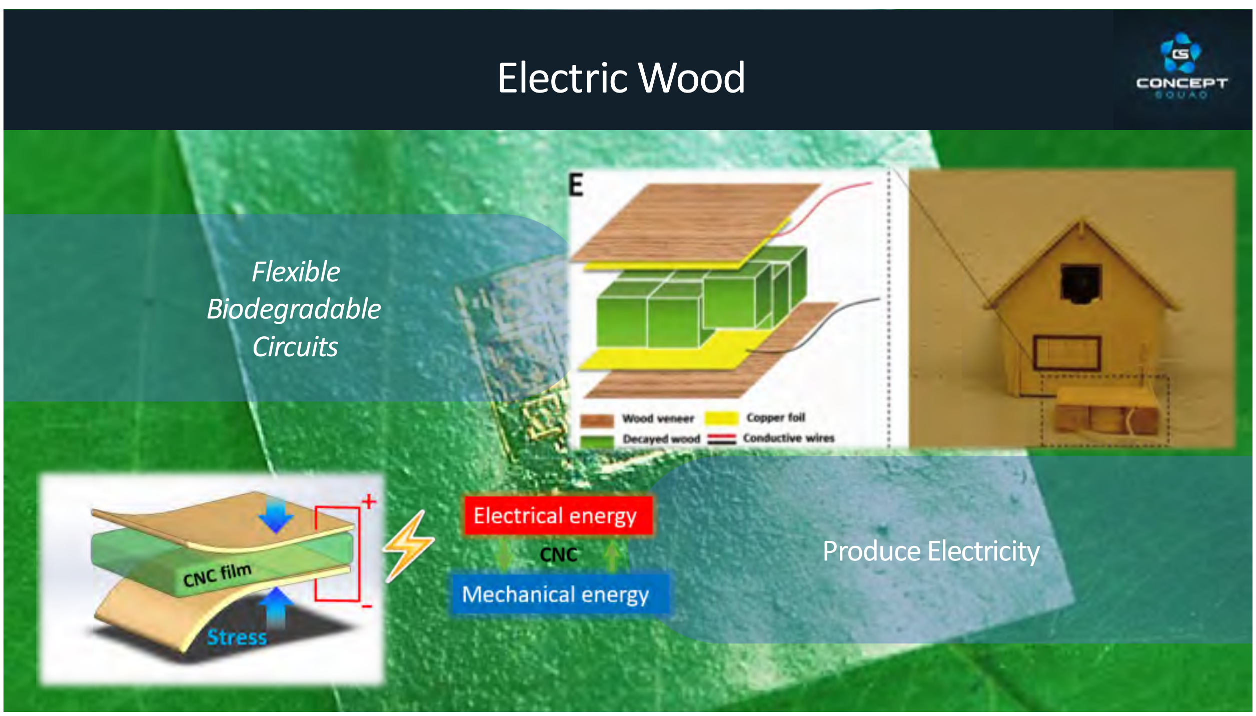
Digital Telepathy

Exocortex


4-D Printing
CONCEPT SQUAD
4D printing is the process through which a 3D printed object transforms itself into another structure

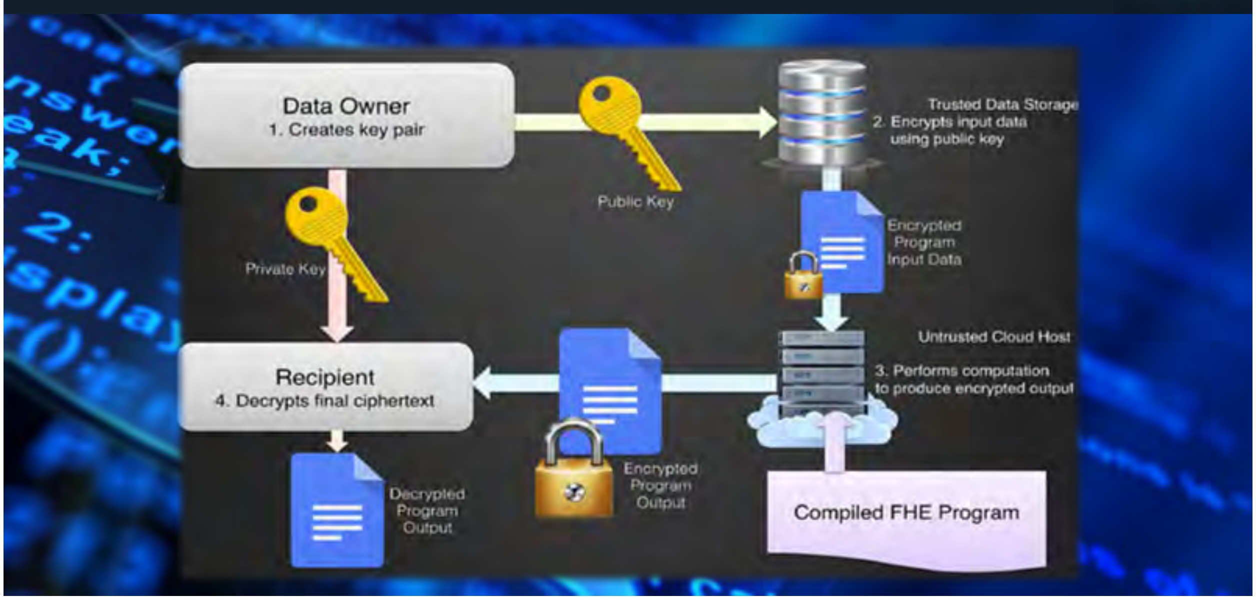

4-D Printing
CONCEPT SQUAD
Growth expected from $62 million in 2020 to $488 million by 2026


Data Storage Glass
CONCEPT
5D OPTICAL DATA STORAGE
45000000 Mb data in a tiny glass disk
ФОНД
ПЕРСПЕКТИВНЫХ
ИССЛЕДОВАНИЙ


Electric Wood
CONCEPT
Flexible Biodegradable Circuits
E
Wood veneer
Copper foil
Decayed wood
Conductive wires
CNC film
Stress
Electrical energy
CNC
Mechanical energy
Produce Electricity

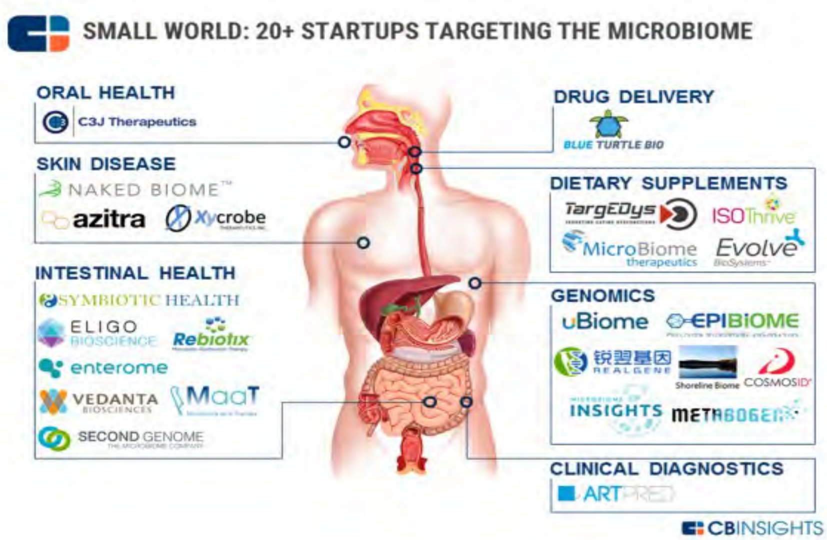
Photophoretic Trap Volumetric Display

Full Homomorphic Encryption

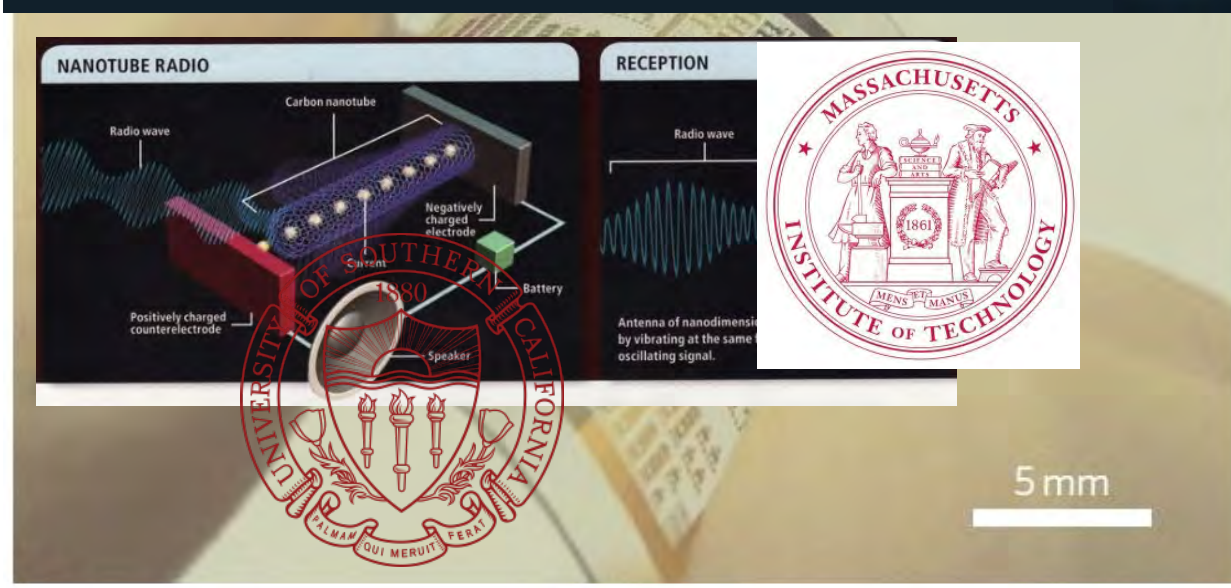


Microbiome

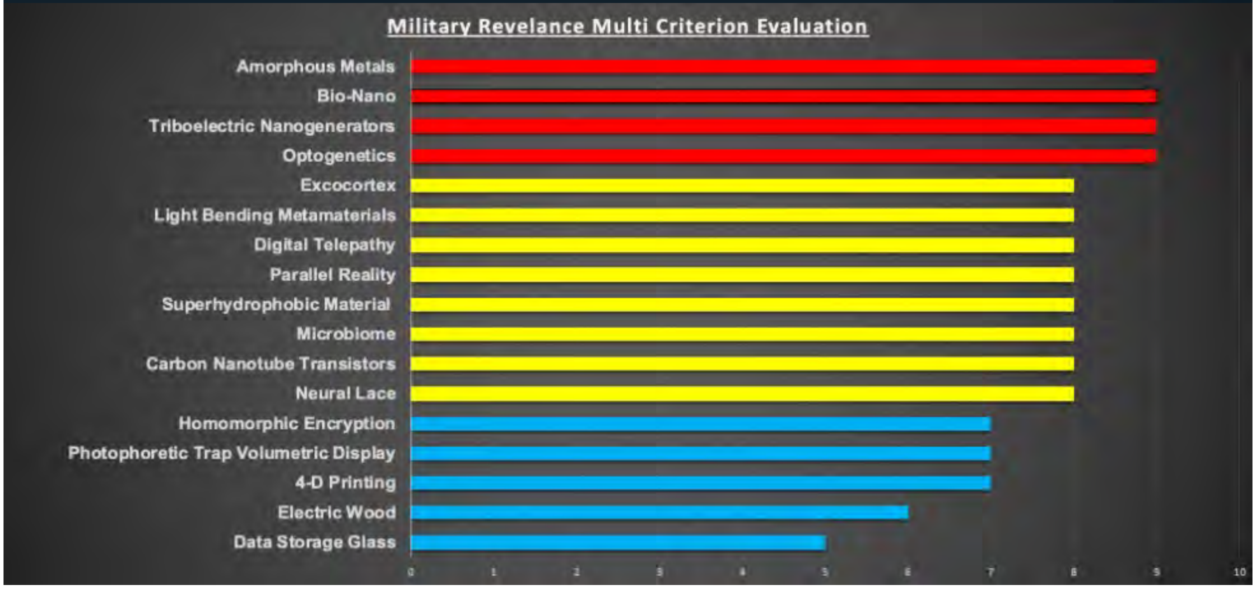
$10 Billion by 2024



Carbon Nanotube Transistors



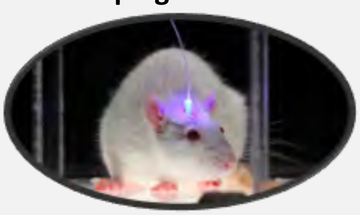
Military Relevance



Military Relevance

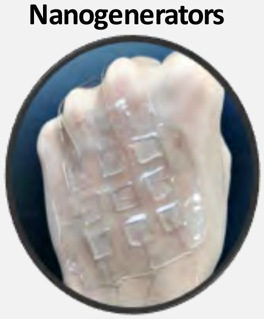
Tier 1

Optogenetics



Bio-Nano Processors

Triboelectric Nanogenerators

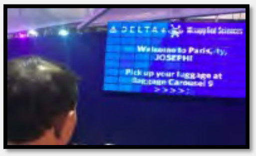


Amorphous Metals

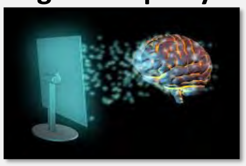
Military Relevance

Tier 2

Parallel Reality

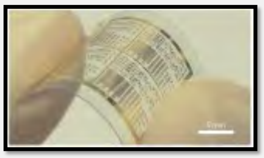


Digital Telepathy

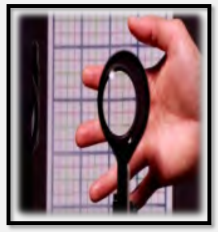


Neural Lace

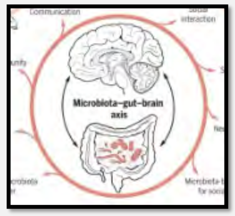
Carbon Nanotube Transistors



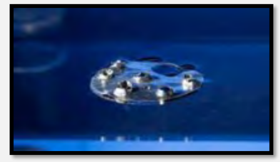
Light Bending Metamaterials



Microbiome



Superhydrophobic Materials



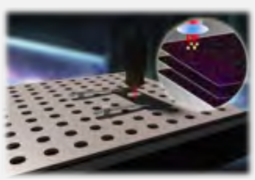
Exocortex

Military Relevance

Tier 3

Fully Homomorphic Encryption

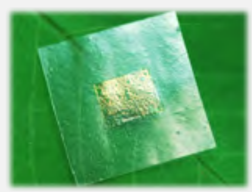
Data Storage Glass



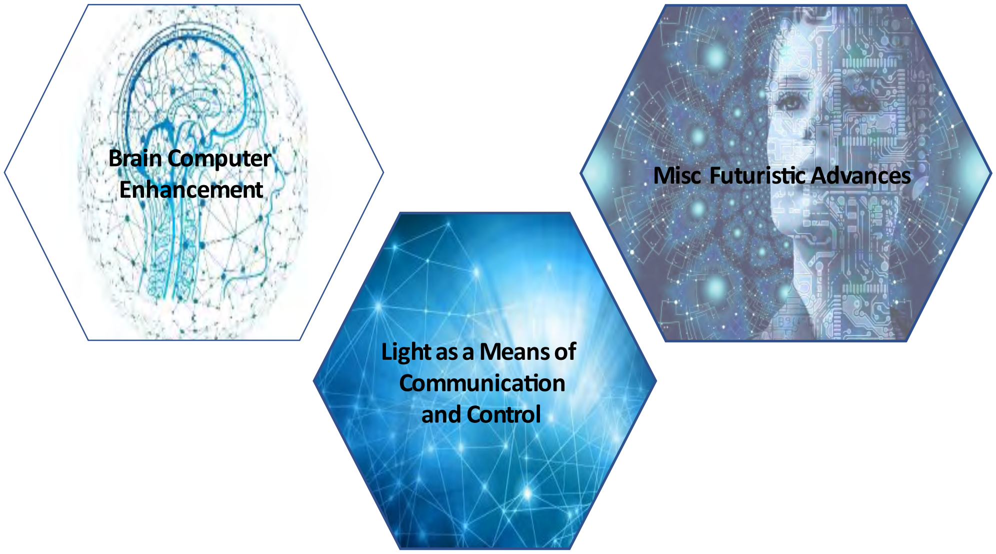
Photophoretic Trap Volumetric Display

4-D Printing

Electric Wood



Convergence



Infrastructure

- Fully operational 6G technology
- Mastery of the terahertz (THz) regime of the electromagnetic spectrum
- Prolongation of smaller, more powerful, and less expensive computing power
- Overall cost -effectiveness

Questions?

Annex H
Master Technology List

Topic	Open Source Results	.mil Results	Remarks
Advance Bacterial Pathogens	3	0	Insufficient time to research
Data storing glass	9	0	
Bio-nano processors	14	0	
Americium battery	593	0	Insufficient time to research
Fourth generation optical discs	6,160	0	Did not meet research definition of surprising
Solar gravitational lens	6,320	0	Did not meet research time definition
Hypertelescope	8,020	0	Insufficient time to research
AB-matter	10,600	0	Research material comes from one single source who is no longer living and theory is highly questioned
Unsinkable Metal	11,300	0	Research led to changing of title to Superhydrophobic Material
Breathing Crystals	15,000	0	Insufficient research material to meet definition
Alcubierre Drive	48,000	0	Did not meet research time definition
Stasis Chamber	60,500	0	Insufficient time to research
Light-bending metamaterials	242,000	0	
Vantablack, darkest material	846,000	0	Insufficient time to research
Designer Babies	4,560,000	0	Did not meet research definition of exciting technology
Multi-material 3D print head	5	1	AFC Table of Future Technologies
On chip particle accelerator	439	1	AFC Table of Future Technologies
Low Latency global video	525	1	AFC Table of Future Technologies
Broadband invisibility cloak	2180	1	AFC Table of Future Technologies
CO2 Harvesting	2510	1	AFC Table of Future Technologies

3-D printed tanks	3550	1	AFC Table of Future Technologies
Metallic Microlattice	5,070	1	Insufficient time to research
Long Range Agumented Reality	10100	1	AFC Table of Future Technologies
Picotechnology	13,100	1	Did not meet research time definition
Sentient Computing	18,100	1	Insufficient time to research (form of ubiquitous computing (2, 680,000 google, 696 .mil)
Foglets (Utility Fog)	25,200	1	Did not meet research time definition
Femtotechnology	25,200	1	Did not meet research time definition
Printed Armor	29300	1	AFC Table of Future Technologies
Living camouflage	32,500	1	Insufficient time to research
Hovertrain	46,100	1	Did not meet research definition of exciting technology
Xenobots	109,000	1	AFC Table of Future Technologies
Universal Computer Memory	252,000	1	AFC Table of Future Technologies
Photonic laser thruster	3,660	2	Insufficient time to research
Beamed power propulsion	4,750	2	Did not meet research definition of exciting technology
Carbon Computing	5430	2	AFC Table of Future Technologies
High temperature superfluidity	6000	2	Insufficient time to research
6G Cellular	7430	2	AFC Table of Future Technologies
Composable Enterprise	9190	2	Insufficient time to research
Very High Speed Compression	12600	2	AFC Table of Future Technologies
Biodegradable Electronics	13,600	2	Insufficient time to research
3-D Printed Skin	14800	2	AFC Table of Future Technologies
Nanowire Battery	18700	2	Insufficient time to research
Molecular Assembler	19500	2	Insufficient time to research

Exocortex	33,500	2	
Nantenna	34500	2	Insufficient time to research
Microfluidics	41100	2	Insufficient time to research
Fusion rocket	66,500	2	Insufficient time to research
Magnonics	74400	2	Insufficient time to research
Carbon Nanotube Field-Effect Transistor	90,900	2	Insufficient time to research
Triboelectric Nanogenerator	135,000	2	
Julia Programming Language	163,000	2	Insufficient time to research
Mass Driver	166,000	2	Insufficient time to research
Secure Access Service Edge	522000	2	Insufficient time to research
Electric Wood	1,160,000	2	
STAP Radar	6050	3	Insufficient time to research
Self-Healing Plastic	6180	3	Did not meet research definition of exciting technology
Precision Guided Firearm	7,620	3	Did not meet research definition of exciting technology
Nanoradio	11,400	3	Research led to changing of title to Carbon Nanotube Transistors
Generative AI	19000	3	Did not meet research definition of exciting technology
Photon Rocket	19,400	3	Insufficient time to research
SAW Sensor	68,900	3	Insufficient time to research
3-D Printed Electronics	71700	3	AFC Table of Future Technologies
Vortex Engine	76500	3	Insufficient time to research
Diamond Batteries	81200	3	AFC Table of Future Technologies
Neural Lace	124,000	3	
Procedural Generation	678,000	3	Insufficient time to research
Quantum Radar	3560	4	AFC Table of Future Technologies
Composite AI	4430	4	Insufficient time to research
Pure Fusion Weapon	14,300	4	Insufficient time to research
Parallel Reality	15,900	4	

Robotic Touch / Feel	16800	4	AFC Table of Future Technologies
LiFi Technology	61,700	4	AFC Table of Future Technologies
Plasma Propulsion	76000	4	Insufficient time to research
Time Crystals	148000	4	Insufficient time to research
Lithium-Sulfur Battery	183000	4	Insufficient time to research
Silicene	243000	4	Insufficient time to research
Health Passport	648000	4	Insufficient time to research
Insensitive Propellant	1,280	5	Insufficient time to research
Metamorphic Manufacturing	1410	5	AFC Table of Future Technologies
Screenless Display	13900	5	Insufficient time to research
Functional Ultrasound	27,000	5	Insufficient time to research
Telepresence	32000	5	Insufficient time to research
Volumetric Display	76,200	5	
Twisted Bilayer Graphene	88,300	5	Insufficient time to research
Information Centric Networking	109,000	5	Insufficient time to research
DNA Computing	229000	5	AFC Table of Future Technologies
Metallic Hydrogen	287000	5	AFC Table of Future Technologies
Electric Double-Layer Capacitor	715000	5	Insufficient time to research
Dynamic Armor	7,020	6	Insufficient time to research
Scramjet Technology	21,000	6	Did not meet research definition of exciting technology
Dynamic Armor	46,000	6	AFC Table of Future Technologies
Spatial Web	48700	6	AFC Table of Future Technologies
Swarm Robotics	64,200	6	Did not meet research definition of exciting technology
Small Nuclear Reactors	87000	6	AFC Table of Future Technologies
Lithium-Air Battery	92900	6	Insufficient time to research
Plasma Weapon	97,100	6	Insufficient time to research
Programmable Matter	107000	6	Insufficient time to research

3-D Metal Printing	211,000	6	AFC Table of Future Technologies
Quantum Internet	358000	6	AFC Table of Future Technologies
Asteroid Mining	886,000	6	Insufficient time to research
Ambient Intelligence	1220000	6	Insufficient time to research
BioInformation	36,400,000	6	Insufficient time to research
Atomtronics	18,900	7	Insufficient time to research
Particle Beam Weapon	38,900	7	Insufficient time to research
Pulse Detonation Engine	49,900	7	Insufficient time to research
Ghost Imaging	108,000	7	AFC Table of Future Technologies
Magnetorheological Fluid	120000	7	Did not meet research definition of exciting technology
Molecular Nanotechnology	124,000	7	Did not meet research time definition
Photophoretic Volumetric Trap Display	205,000	7	
Responsible AI	332000	7	Insufficient time to research
Light Bending Metamaterials	858,000	7	
FBAR Sensor	2900	8	Insufficient time to research
Microbiome Research	64,000	8	
Ion Propulsion	140000	8	Insufficient time to research
Nanoelectromechanical Systems	161000	8	Insufficient time to research
Spatial Computing	227,000	8	Insufficient time to research
Amorphous Metal	241,000	8	
4D Printing	305,000	8	
Bioprospecting	693,000	8	AFC Table of Future Technologies
Artificial Gravity	695,000	8	Insufficient time to research
Data Fabric	938000	8	Insufficient time to research
Zero Point Energy	1060000	8	AFC Table of Future Technologies
Optogenetics	1,120,000	8	
Fusion Power	2610000	8	Insufficient time to research
Bioplastic	3940000	8	Insufficient time to research
Rotating Detonation Engine	27,200	9	Insufficient time to research
Micromirrors	115000	9	Insufficient time to research

Nanoelectromechanical Systems	196,000	9	Insufficient time to research
MIMO Radar	204,000	9	Insufficient time to research
Nano Fabrication	284000	9	AFC Table of Future Technologies
Conductive Polymers	606,000	9	Insufficient time to research
Magnetic Nanoparticles	606000	9	Insufficient time to research
Hyperloop	5460000	9	AFC Table of Future Technologies
Quantum Dots	5990000	9	Did not meet research definition of exciting technology
Cryogenic Treatment	135	10	Insufficient time to research
Distributed Propulsion	39,900	10	Insufficient time to research
Fully Homomorphic Encryption	803,000	10	
General Adversarial Networks	976,000	10	Insufficient time to research
Extended Reality	870000	128	AFC Table of Future Technologies
Explainable AI	429000	194	Insufficient time to research
Self Healing Materials	204000	214	AFC Table of Future Technologies
Holodeck	3060000	265	AFC Table of Future Technologies
Memristor	660,000	283	Related topic to neuromorphic computing
Neuromorphic Computing	320,000	329	
Telepathy	24000000	398	AFC Table of Future Technologies
Ocean thermal energy conversion	494000	492	Insufficient time to research
Haptics	3,700,000	631	Did not meet research time definition
Smart Materials	621,000	634	AFC Table of Future Technologies
Biodegradeable Sensors	3,920	696	Research led to changing of title to Medical Biodegradable Sensors (increased .mil search results)
Optical Computing	293000	919	AFC Table of Future Technologies
Aerogel	4930000	1020	Insufficient time to research
Spintronics	1,590,000	1070	Insufficient time to research

Edge Computing	7,290,000	1150	AFC Table of Future Technologies
Plasmonics	1,400,000	1160	Insufficient time to research
Fullerene	5020000	1260	Insufficient time to research
Hyperspectral Imaging	334,000	1400	In AFC Table of Futures as Quantum computing / quantum
Smart Grid	11800000	1410	Insufficient time to research
Quantum Cryptography	1,490,000	1540	Insufficient time to research
Autonomous Robots	1670000	1590	Insufficient time to research
Superalloy	1360000	2140	Insufficient time to research
Synthetic Data	2,000,000	2640	
Biofuel	12400000	2700	AFC Table of Future Technologies
Blockchain	142000000	2800	AFC Table of Future Technologies
Graphene	38,900,000	3570	Insufficient time to research
Direct PC to Brain interface	19300000	4670	AFC Table of Future Technologies
Deep Learning (Deep Neural Nets)	429000000	4880	Related topic to neuromorphic computing
Distributed (disbursed) Computing	6,670,000	5310	Insufficient time to research
Time Travel	41600000	6890	AFC Table of Future Technologies
Force Fields	5700000	9350	AFC Table of Future Technologies
Social Distancing Technology	43700	26200	Insufficient time to research
AI Augmented Development	29500	29500	Insufficient time to research

Annex I
Cover Graphic Sources

Science Focus, https://www.sciencefocus.com/future-technology/future-technology-22-ideas-about-to-change-our-world/

Scientific American, https://www.scientificamerican.com/article/will-artificial-intelligence-ever-live-up-to-its-hype/

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Channel Life, https://channellife.com.au/story/quantum-technology-holds-huge-potential-in-australia-report

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MarTech Today, https://martechtoday.com/smart-marketing-still-hinges-on-humanity-not-technology-213413

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Scientific American, https://www.scientificamerican.com/article/will-artificial-intelligence-ever-live-up-to-its-hype/

Genetic Engineering and Biotechnology News, https://www.genengnews.com/category/magazine/126/

CONCEPT
SQUAD