PREPARING FOR QUANTUM WARFARE

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Abstract

In the ever-evolving realm of present day warfare, the emerging and disruptive technologies play a vital role in shaping of military strategies. In this context, it is imperative that military commanders at all levels must be conversant with new developments in technological domain to maintain a right balance of weapons, equipment and the warfighters. One such emerging and potent technology is Quantum Technology which has seen tremendous focus in the recent past. Quantum technologies are proving to be very potent for military domain, promising to provide technological capabilities far beyond the present landscape. The technology is already on the path towards revolutionising the fields of Quantum Computing, Quantum Sensing, Quantum Communications, Quantum Imaging and Quantum Navigation. Quantum technologies for specific military applications, introduce new capabilities, increasing effectiveness and improving precision and have led to the emergence of 'quantum warfare'.

In the article, we take a glimpse of the quantum technologies, understand their importance for our armed forces and explore major defence applications. A brief review of the initiatives taken for indigenous development of the technology has been carried out with recommendations to address the global challenge of Quantum Warfare.

Introduction

Quantum technology is an upcoming field of applied physics and engineering, which harnesses the properties of quantum mechanics and unique phenomena like quantum superposition, quantum entanglement and quantum tunneling.

A quantum is described as the smallest measurable quantity of matter or energy. Thus, in case of electricity, a quantum is an electron and in case of light, a quantum is a photon. Classical physics and Newton's laws of motion can accurately explain the behaviour of objects that are larger than atoms and molecules. However, classical physics goes wrong in explaining the behaviour of sub atomic particles. The advent of Quantum physics has not only resolved the imbroglio but has also led to the development of all powerful Quantum Technologies.[1]

Dual Behaviour of Matter and Radiation

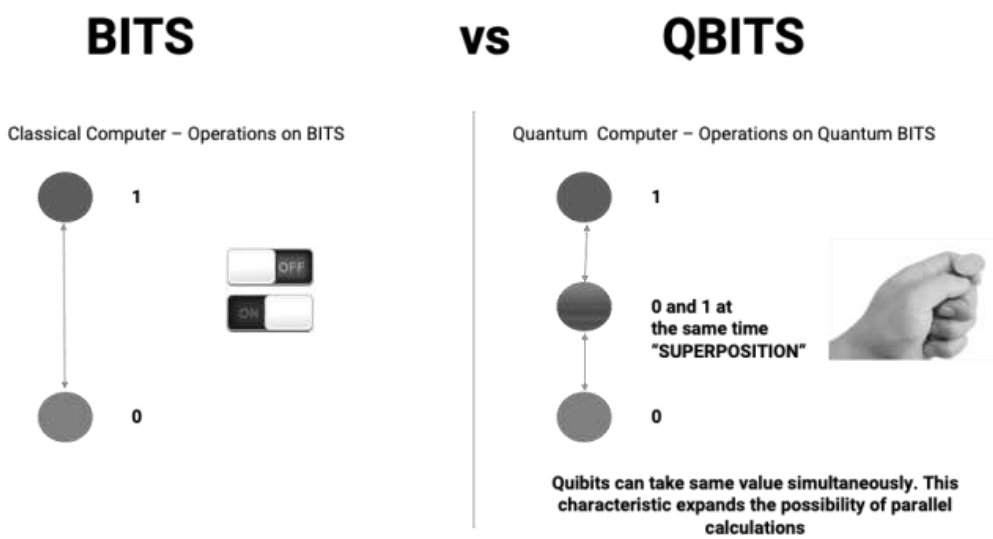
Sub-atomic particles like electrons, being matter, exhibit particle like behaviour. However, simultaneously they also exhibit wave nature. Particles larger than atoms also have associated wave nature but the wave component is negligible due to large mass. The sub-atomic particles have very small mass and hence both particle and wave like behaviour are dominant in them. This is known as dual behaviour of particles and defined by De-Broglie relationship, a mathematical explanation of the phenomena. Dual nature is not only applicable to sub atomic particles but also applicable to electromagnetic radiation. EM waves demonstrate the properties of wave as well as of particle. According to electromagnetic wave theory, the energy is emitted or absorbed continuously whereas, according to Plank's theory, energy is emitted or absorbed discontinuously i.e. in packets called Quantas.[2]

Some unique phenomena of Qauntum Technology which are harnessed for the applications are briefly explained in the succeeding paragraphs.

Quantum bit or Qbit

In conventional computing, coding of data is carried out using a binary bit, which takes the values of "0" or "1" at a time. In Quantum technology, the basic unit of information is a quantum bit or Qbit. A qubit is a two-level system, which can attain two values of any physical property. There can be many systems which can qualify as a Qubit. A quibit can be an electron in which its spin in two opposite directions can be considered as two values. Similarly, in case of a photon, its polarization degree can have two values, say, horizontal and vertical.[3]

A qubit uses the quantum property of superposition to be simultaneously in two states. A qubit can signify '0' and '1' at the same time and a system having two qubits can represent four states at the same time (00, 01, 10, 11). Consequently, quantum computing of a two qubit system will be four times faster than a two bit classical computing. Accordingly, In case of 'n' bits, the speed will increase to 2^n times. If n =56, then 2^56 is of the order of 'Trillions'. It is expected that quantum computers, in future, may be million times faster than a super computer.



Source: Properties of Quantum Computing, Drishti IAS,
URL: https://www.drishtiias.com/mains-marathon-daily-answer-writing-

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Superposition

In quantum technology, a phenomena that permits quantum objects to simultaneously exist in more than one state is known as Superposition. This implies that an object can be in two states at the same time while remaining a single object. Superposition permits the qubits of the quantum technology to carry out multiple simultaneous operations, making them exponentially faster than classical computers. Superposition enables quantum algorithms to perform operations in a much shorter time as compared to the conventional supercomputers to solve certain problems.[4]

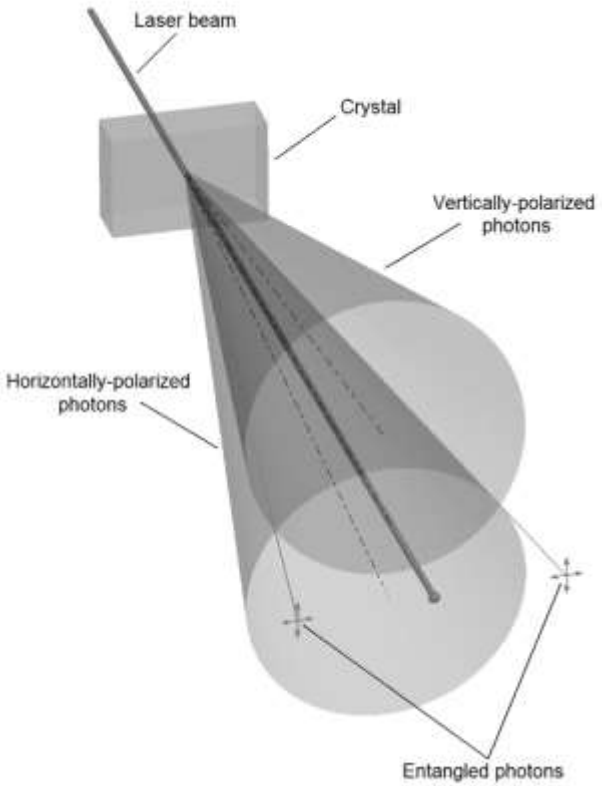
Quantum Entanglement

Quantum entanglement is an occurrence in which two or more subatomic particles interact with each other in such a way that that their quantum states get dependent on each other. The particles continue to remain entangled even when they move away and are large distance apart.[5]

Entanglement can take place between quantum particles like electrons or photons. When this happens, the state of one particle gets dependent on the other. Any change in the state of one particle has instant effect on the other whatever may be the distance between them. This phenomena is a very important aspect in quantum information technologies.

There are many methods which have been invented for achieving quantum entanglement. For example one popular method of achieving quantum entanglement of two photons is 'Spontaneous Parametric Down Conversion' which is explained in the diagram below.[6]

Spontaneous Parametric Down-Conversion



Source: Logan P. Kaelbling , Production of Entangled Photons via Spontaneous Parametric Down-Conversion, URL:https://digitalcommons.bard.edu/cgi/viewcontent.cgi?article=1359&context=senproj_s2020#:~:text=Spontaneous%20parametric%20down%2Dconversion%20is,converted%20photons%20in%20its%20place/

This spontaneous parametric down-conversion diagram illustrates a Laser beam passing through a crystal's optical axis which leads to photons' diffractions and polarizations leading to quantum entanglement. Measurements carried out on entangled photons proved beyond doubt that the properties were perfectly interrelated.

Nobel Prize for Physics for the year 2022 was awarded to three scientists John Clauser, Alain Aspect and Anton Zeilinger for their work in quantum entanglement, who experimentally proved and validated the phenomena. This phenomena has proved to be

very useful in reducing the time for processing information transfer between qubits. Long back in 1935, this phenomena was demonstrated to Einstein, who called it "a spooky action at a distant" as it was against the laws of classical physics.[7]

Quantum Computing

Quantum computers utilise the unique principles of quantum science to achieve very high computational power and ability to store huge volumes of data. They are proving to be exceptionally advantageous and faster than conventional supercomputers for certain type of tasks.

Present day computers encode data using binary bits which can be either "0" of "1" at a time. As we have seen, the basic unit of memory in a quantum computer is a quantum bit or qubit. Quantum bits can acqure many arrangements simultaneously. Qubits can also get into quantum entanglement and can represent different information at the same time.

For example, a conventional computer requires eight bits for representing any number between 0 and 255. However, eight qubits can represent every number between 0 and 255 at the same time. A 100-qubit quantum computer can carry out more than 1,000 billion billion billion simultaneous calculations. Where there are large number of possible combinations, quantum computers can process them simultaneously. On the other hand, there are certain other types of computing where classical computers will continue to perform better in the immediate future.[8]

As of now, quantum computers are very noisy and sensitive to the environment. The present day quantum computing technologies are being called Noisy Intermediate-Scale Quantum Computing (NISQ). Sensitivity to electromagnetic fields, heat, and collisions with air molecules can cause a qubit to lose its properties and collapse. This phenomena is called quantum decoherence and may cause a system to crash. The problem is more severe as the number of qubits increase. Quantum computer components are being designed to protect the qubits from interferences by shielding and keeping them at very low temperatures.

Just as in conventional computers, quantum computers consist of hardware and software. There are three main constituents of quantum hardware. The data plane is the core of the quantum computer and houses qubits. The control plane performs the task of transferring signals to qubits. The control processor plane runs programs. The host processor interacts with the quantum software and sends signals to the control and measurement plane.

Quantum software runs quantum algorithms using quantum circuits. Developers use software development tools and libraries to code quantum algorithms.

Types of Quantum Technology

Rapid advancements are taking place in the development of quantum technologies. Efforts are on to take the quantum computers from the present day NISQ level to fault tolerant computers. Brief example for some of the qubit technologies are given in the succeeding paragraphs.[9]

Gate Based Ion Trap Processors use charged atoms (ions) based qubits which are housed on micro fabricated trap controlled by electric field and managed by laser beam. They work more efficiently at cryogenic temperatures. Gate Based Superconducting Processors use qubits built on superconducting circuits which also work on cryogenic temperatures. Other technologies being used are Photonic Processors using light pulses, Neutral Atom Processors which work at room temperature, Rydberg Atom Processors and Quantum Annealers which allow larger number of qubits in the system compared to other methods.

Military Applications of Quantum Computers

Applications where quantum computers are making considerable impact and their upcoming military usage are discussed in succeeding paragraphs.[10]

- **Quantum Computing.** Military applications of Quantum Technology are under research and development. Quantum computing is one of the areas which is considered capable of exponentially increasing the speed and computing power. The storage and computing of large volumes of data is likely to be much more

efficient as compared to conventional computers. This can have a very positive influence on military operations, due to the ability of quantum computers to process colossal amounts of data with speed and precision. It is also likely to enhance the capabilities of Big Data Analysis which is again very important for the defence forces.

- **Quantum simulation.** Quantum computers are highly efficient for modeling as they employ quantum technologies in their computation. They are more capable of dealing with complex and ambiguous problems compared to conventional computers. Thus, they can be very gainfully employed to augment our capabilities in war gaming and constructive simulation.

- **Cryptography.** Complex algorithms used in cryptography can be implemented with greater efficiently using quantum computers. This will also provide more capabilities in breaking of crypto algorithms providing opportunities as well as challenges.

- **Optimization.** It is the method of arriving at the most optimum solution to a problem with given inputs and desired outputs. The method is used for critical decision making. For example, the factors can be manpower, cost, quality, and time. The factors can be optimized for an optimum output. Using quantum based algorithms, solutions have been found which were earlier not feasible. There is tremendous scope for using quantum optimization in sensor deployment, target detection, transportation, logistics and defence production.

- **Quantum machine learning and AI.** Quantum technology provides the potential of enhanced machine learning and more efficient AI.

- **Search.** Quantum algorithms are tremendously speeding up searches of unstructured data, carrying it out in lesser steps compared to traditional algorithms.

Quantum Communications

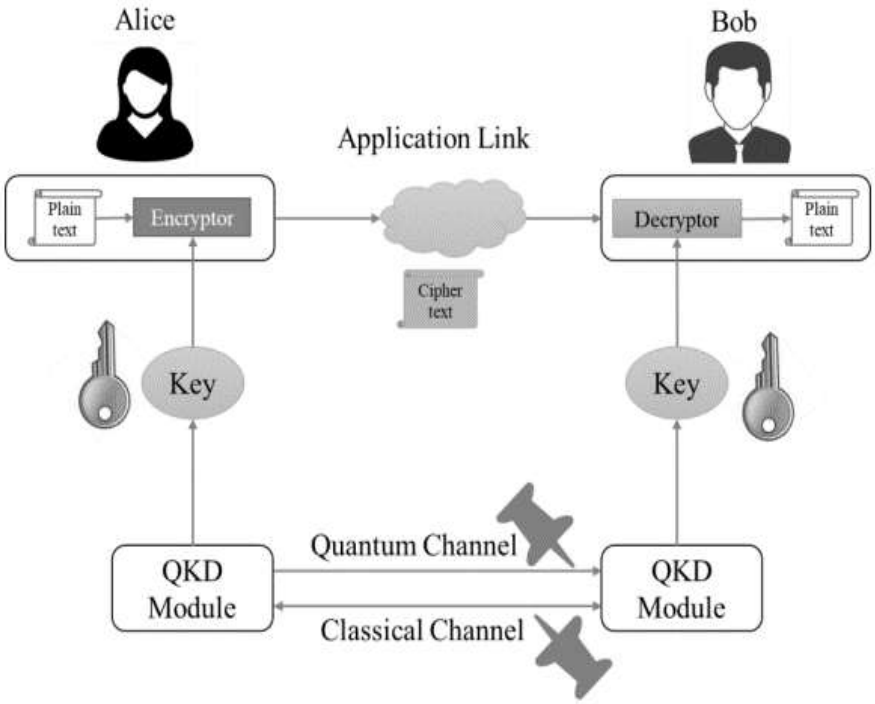
Quantum communication is a promising and rapidly growing field of quantum technology which takes advantage of quantum principles to provide high level of data security. Quantum information exchange is achieved by using a photon as qubit as the carrier of data and transmission of quantum states. Commonly used channels for information exchange are low loss optical fibre cable or free space channels.

The high level of security is provided by using the property of fragile nature of entangled photons or qubits. In case these entangled qubits are interfered with, they immediately collapse to zero state and carry not information further. Thus the receiver detects the interference and the qubit is rejected. In effect, if a hacker tries to tamper with a qubit, the network will get alerted.[11]

We will discuss some underlying technologies which make quantum communications highly secure and resilient.

Quantum Key Distribution

The conventional encryption systems with asymmetric encryption keys are vulnerable to hacking. QKD provides solution to the problem as it is considered to be super secure. In QKD system, only the encryption keys are sent in quantum state using qubits. Once the keys are perfectly shared, the encrypted data is transmitted using classical bits over insecure networks.



Source: Quantum Key Distribution Source: Martin Giles, "What is Quantum Communication?", MIT Technology Review, 14 Feb 2019. https://www.technologyreview.com/2019/02/14/103409/what-is-quantum-communications/

There are many protocols which have been developed for QKD. BB84 is one such QKD which is already in use. Understanding its working will clear the concept of QKD. Suppose, there are two persons Alice and Bob. Alice wants to transmit information securely to Bob. For this, she generates an encryption key as sequence of qubits which are sent to Bob through a quantum channel and measurement data through classical channel. With this information, he is able to decode the key. In case there is any attempt to intercept the signal, some of the qubits collapse and the receiver gets alerted. In that case they reject the key and generate a new key and accept only when there is no indication of attempt to intercept. Alice can now encrypt the data with her keys and send it in classical bits to Bob, who, in turn decodes the data with his keys.[12]

There are a number of QKD networks being establish world over. China has established the longest link extending over 2,032 km from Beijing and Shanghai. In the US, a company named Quantum Xchange has been tasked to establish a 500 miles link of OFC along the East Coast to create a QKD network. The project will link Manhattan with New Jersey.

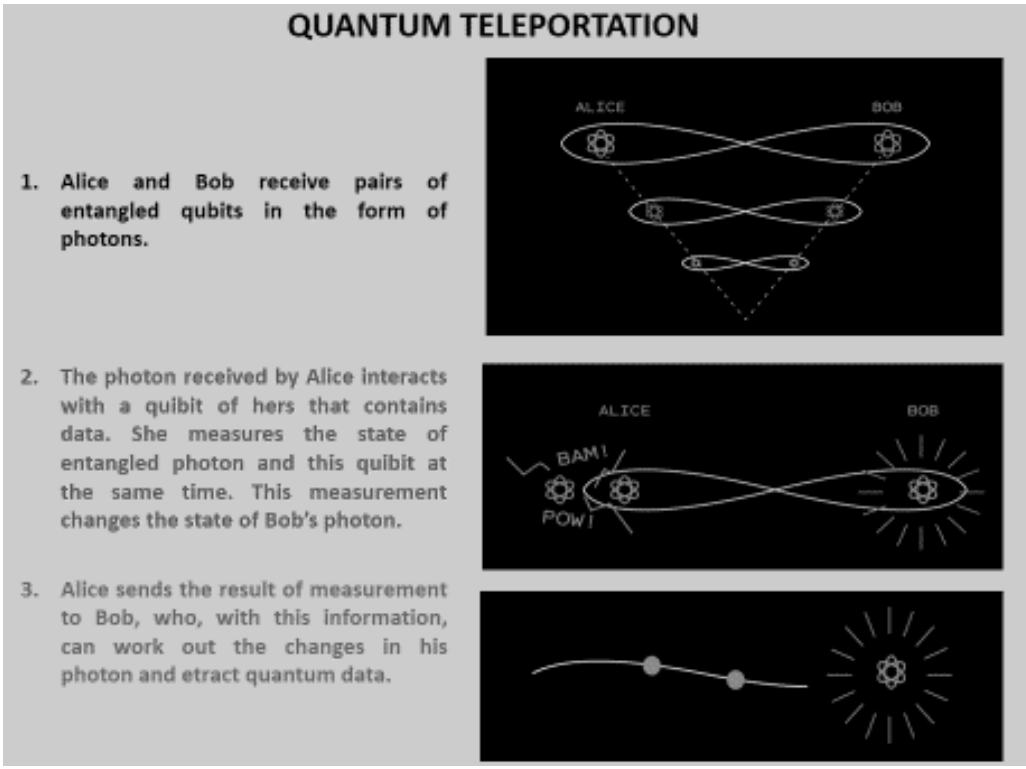
Quantum Repeater

Due to absorption of photons in OFC, the range of communications gets restricted. Hence repeaters are required along the cable to amplify the signal. QKD networks also need to establish "trusted nodes" at various points. The Beijing-to-Shanghai network has 32 such nodes. At these nodes, quantum keys are decrypted and then re-encrypted in a new quantum state for transmission to the next node and here lies the vulnerability. A hacker can copy the decrypted keys without leaving a trace.[13]

The above vulnerability can be overcome if we use quantum repeaters where quantum processors enable the keys to remain in quantum form while they are amplified and retransmitted. Such repeaters have been created in the labs, but no working model has so far been deployed. To take care of the QKD vulnerabilities, there is another very advanced solution called quantum teleportation.

Quantum Teleportation

Quantum teleportation is a very innovative technology for transmitting data in pure quantum form. This technology is based on the principle of quantum entanglement. Here, entangled photons pairs are created. One photon of this pair is transmitted to Alice who is sender of data and the second photon is transmitted to Bob, the receiver. Alice, on receiving her entangled photon, allows it to interact with a "memory qubit" that houses the data to be transmitted to Bob. This exchange alters the state of her photon, and since Bob has the entangled photon, its state also changes simultaneously. Thus, the data in Alice's memory qubit from her photon is "teleported" to Bob's photon from where it is extracted. The graphic below lays out the process:[14]



Source: Martin Giles, "What is Quantum Communication?", MIT Technology Review, 14 Feb 2019. https://www.technologyreview.com/2019/02/14/103409/what-is-quantum-communications/

The technology is complex and poses many challenges. However, tremendous efforts are being made as it promises great benefits in quantum communications.

Quantum Internet

Quantum internet will be similar to conventional internet with the difference that it will be supported by quantum communication network. Quantum internet is not likely to replace the entire present day internet. Conventional internet will continue to be used for not very sensitive information and quantum internet will be used for data requiring high grade of security.

China is making very fast progress in quantum technologies and quantum network. It launched Micius, a quantum communication satellite and through this satellite, they demonstrated world's first video conference secured by QKD between Beijing and Vienna as long back as 2017. They have linked one ground station connecting the satellite with Beijing to Shanghai terrestrial network[15]

Free Space Quantum Communications

The free-space quantum channel is more challenging compared to optical fibre. The ranges of optical photons are limited in free space due to strong atmospheric attenuation. Hence, the commonly established quantum networks make use of quantum satellites as the losses in satellite–ground link is lesser compared to the loss between two ground stations at a distances. Optical photon communication in free space for short distances is possible with the use of drones. Information is transmitted using the method of Quantum Teleportation.

Quantum Sensing

Quantum Sensing is advanced sensor technology that uses the principles of quantum physics. It harnesses the unique quantum phenomena like superposition and entanglement. It greatly improves the accuracy of measurement as data is collected and analysed atomic levels. The sensing is carried out by detecting changes in electric, magnetic fields, and motion.

Collecting data at the atomic level involves extracting information from individual atoms. This enables quantum sensors to be exceptionally accurate, highly detailed and extremely efficient. They are also much more reliable than conventional sensors being less susceptible to jamming and other electromagnetic interference.

Quantum Sensing Fundamentals

There are many quantum technologies which support and enable quantum sensing. These are being discussed below.[16]

- **Superconducting circuits. S**uperconducting Quantum Interference Devices (SQUIDs) are sensing devices which have already been developed and are basis for basis of most sensitive magnetometers. However, they require cryogenic cooling.
- **Atoms and ions.** Atoms contained in an atomic vapor cell or magneto-optical trap (MOT) and ions in a RF trap are used for sensing. These are being used in compact atomic clocks and optically pumped magnetometers (OPMs) Wideband RF sensors use Rydberg states of atoms. MOT is also being used for gravity sensing.
- **Quantum time-keeping and clocks** technologies are vital for communication and navigation.
- **NV diamonds generated qubits** offer the potential for sensing operation at room temperature.
- **Quantum photonics** using single photon are providing increased sensitivity.

Quantum Sensing Applications in Defence

Situational awareness is an extremely important factor on the battlefield which provides the ability to visualize the environment, develop a Common Operating Picture, assess enemy threats, and take informed decisions. Presently, the conventional surveillance devices like radars, satellite imagery, optical and thermal imagers are networked together on the battlefield to achieve data fusion. However, these systems are vulnerable to jamming and interference.

The development of quantum sensing technologies have potential to exponentially enhance the situational awareness capabilities. Quantum sensors will help overcome the complexities and vulnerabilities of present day systems and will provide better accuracy, higher sensitivity, and enhanced ranges. The new capabilities will be more robust and resilient. For example, in the PNT (Positioning, Navigation & Timing) technology, the use of cold atom- based systems provide capability to accurately navigate in GPS denied environment.

There are abundant possibilities of using quantum sensing techniques in defence domain. The potential is diverse and unlimited, though presently there are challenges which need to be overcome. Quantum sensors have the potential of detection, identification and tracking of targets like stealth submarines, providing early warning of ballistic missile launches, providing ultra-accurate navigation etc. Quantum gyroscopes and accelerometers carry out highly precise measurements, thus providing accurate guidance in GPS-denied environment.

Quantum Inertial Navigation is an important quantum sensing application in the defense domain. Our adversary China is known to have developed counter space capabilities including GPS jamming. Our defence forces are heavily dependent on GPS for navigation. In a GPS denied environment, the navigational capabilities will be seriously impacted. Also GPS navigation is not available in underground and underwater areas. To cater for this, Inertial Navigation Systems are provided for military aircrafts, missiles, naval vessels and ground vehicles. INS works by continuously calculating acceleration and rotation to determine location. However, these measurements have certain errors which accumulate over a period of time. Hence they require frequent calibration. INS drifts by about 1,8 km per day for ships and 1.5 km per hour for aircrafts. Quantum sensors promise to overcome the drawbacks of the INS with exceptionally high measurement accuracy. Quantum accelerometers are found to be 50 times more accurate than conventional accelerometers.[17]

Portable MRI Systems based on Quantum technology use Optically Pumped Magnetometers (OPM) working at cryogenic temperatures. Field deployable version of this equipment is very well suited for treatment of solders in remote operational areas.

Small Sized Ultra Wideband RF Sensors use the quantum technology of Rydberg atoms. US companies, BAE and Infleqtion are developing a 1 cm3 RF sensor capable of detecting signals from 10MHz to 40Ghz.

Gravity Sensing detects changes in gravity gradient, thereby any voids get detected. It uses cold-atom technology. Its ability to detect air pockets underwater and underground is leading to detection of submarines and also IEDs and underground tunnels.

Quantum Warfare

Quantum technologies have the potential to revolutionize the military technological capabilities by bringing in enhanced precision, increased effectiveness and redefining the future warfare. Realizing its importance for the military domain, there has been an increased emphasis on development of these technologies. There appears to be a race amongst the major powers for developing quantum technology as it is leading us into a new technological revolution. Quantum technologies are finding scope for application in entire military domain and spectrum of conflict. The growing competition in this field is emerging as Quantum Race for science & technology and Quantum Warfare for the military. A paradigm of Quantum Warfare is shown in the figure below:

Source: Author

United States passed the National Quantum Initiative Act in 2018 to give boost to quantum R&D. Realising its importance, other counties like Russia, Germany, the UK, France and Canada have also started investing in quantum technologies. China has taken a lead in

development and have achieved important milestones. Under the program Quantum Experiments at Space Scale (QUESS) they launched a satellite solely for quantum communication in the year 2016. They have reported success in quantum teleportation, world's first quantum router and setting up quantum-encrypted government network. They have plans to establish a satellite-based quantum communication network.[18]

To remain in the race, India has also made a beginning in development of this technology. Government of India announced National Quantum Mission in April 2023 and allocated an amount of Rs. 7000/- crores for this purpose. NQM has laid down timelines for development of various quantum technologies.

Other initiatives to provide impetus to Quantum Technologies include:-

- Quantum Computing Applications Lab (QCAL) was established by Ministry of Electronics and Information Technology (MeitY) to work in the areas of quantum computing.
- The National Mission on Quantum Technologies and Applications (NM-QTA) was started in 2020 by Department of Science and Technology for developing quantum technology eco system.
- Prime Minister's Science and Technology Innovation Advisory Council (PM-STIAC) has been set up for Quantum Technologies & Applications.
- Quantum Measurement and Control Laboratory (QuMaC) is working for the development of superconducting and nanofabricated electrical circuits to produce quantized "artificial atoms"..
- In Indian Army, a Centre of Excellence has been set up at MCTE, Mhow.
- ISRO's Space Applications Centre (SAC), Ahmedabad, in Sep 2023, successfully established free-space QKD at 300 mtrs, which is a major breakthrough.
- Recently, a joint team OF DRDO and IIT Delhi demonstrated QKD link over OFC.

Though India has made a beginning, it has to go a long way for keeping pace with our adversary China. Focused and sustained efforts are required to speed up the progress. Also, cooperation amongst all agencies are required to achieve synergy at national level to be "Quantum Ready".

Way Ahead

Quantum technologies are ushering in a technological revolution which can change the nature of warfare. This offers us tremendous opportunities and also pose many challenges. For example, unless we upgrade, quantum computers will be able to break the classical cryptography with ease posing serious threat to national security. [19]

Some recommendations in this regard are given below.

- Maximum emphasis needs to be given to indigenous development with public – private partnership including SMEs, startups and academia.
- Being dual use technologies, there is need to synergise the efforts, within the armed forces, amongst government R&D organisations, PSUs and Industry.
- A focused approach is required for development and manufacture of Quantum hardware as this is a weak area for our country. Cooperation for sharing of knowledge with friendly foreign countries is a must.
- Joint missions and projects with countries for development of systems and projects will be of great help.
- Development of common facilities within the country like infrastructure for simulation and testing is needed.
- Capability building and training should include workforce development, training programs and international cooperation.
- Centres of Excellence for Quantum Technologies must be identified and adequately supported.

- Realistic timelines and monitoring of development must be instituted.
- Enhanced Government funding is the requirement which should be duly prioritized, judiciously granted and monitored.

Conclusion

Quantum technologies have huge potential to exponentially enhance the capabilities of computing, cyber warfare, sensing, navigation, autonomous weapon systems, cryptography, radars, EW and provide highly secure communications. It is evident that this technology is a great enabler of military power. Hence, there is now a race amongst the leading nations of the world to develop these technologies and their military applications. It is therefore a must that India also gets into this race and all out efforts are made to develop these technologies to remain militarily powerful.

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Major General AK Srivastava, VSM (Retd), has commanded a Signal Regiment in the sensitive Akhnur Sector of Jammu and Kashmir, along the Line of Control. His staff exposures include DAA&QMG of a Mountain Brigade in the North East, Assistant Military Secretary (AMS) in Military Secretary's Branch, Colonel Adm of an Infantry Division in the desert sector during Op PARAKRAM and Planning Officer (Electronics) in MoD. His qualifications include M. Sc Physics (Electronics), Fellow, Institution of Electronics and Telecommunications Engineers, M. Sc. Defence & Strategic Studies, M. Phil Defence & Management Studies, M. Phil Social Sciences and Advanced Communications Course in Signals Academy Leningrad, USSR, (Now St. Petersburg, Russia).

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