ISSN 1831-9424

JRC SCIENCE FOR POLICY REPORT

Identifying future critical technologies for space, defence and related civil industries

A technology foresight exercise to support further EU policy developments

Farinha, J., Vesnic-Alujevic, L., Hristova, M.

2023

EUR 31688 EN

This publication is a Science for Policy report by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The contents of this publication do not necessarily reflect the position or opinion of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication. This report is based on research of the JRC. It does neither include any information or data collected in the context of the EU Observatory of Critical Technologies, nor does it prejudge the future work of the Observatory. For information on the methodology and quality underlying the data used in this publication for which the source is neither Eurostat nor other Commission services, users should contact the referenced source. The designations employed and the presentation of material on the maps do not imply the expression of any opinion whatsoever on the part of the European Union concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

Contact information
João FARINHA
Unit S.1 EU Policy Lab: Foresight, Design and Behavioural Insights
Joint Research Centre, European Commission, Brussels, Belgium
joao.farinha@ec.europa.eu

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC 134926

EUR 31688 EN

PDF ISBN 978-92-68-08221-8 ISSN 1831-9424 doi:10.2760/005929 KJ-NA-31-688-EN-N

Luxembourg: Publications Office of the European Union, 2023

© European Union, 2023

The reuse policy of the European Commission documents is implemented by the Commission Decision 2011/833/EU of 12 December 2011 on the reuse of Commission documents (OJ L 330, 14.12.2011, p. 39). Unless otherwise noted, the reuse of this document is authorised under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence (https://creativecommons.org/licenses/by/4.0/). This means that reuse is allowed provided appropriate credit is given and any changes are indicated.

For any use or reproduction of photos or other material that is not owned by the European Union permission must be sought directly from the copyright holders. The European Union does not own the copyright in relation to the following elements:
- Cover page illustration, Photo by SpaceX on Unsplash
- Page 04, Photo by Alexey Larionov on Unsplash
- Page 12, Photo by Steve Jurvetson on Wikimedia Commons
- Page 17, Photos by Westinghouse Electric Company
- Page 21, Photo by LioniX International
- Page 28, Photo by SpaceX on Unsplash
- Page 34, Photo by Manuel on Unsplash

How to cite this report: Farinha, J., Vesnic-Alujevic, L., Hristova, M., *Identifying future critical technologies for space, defence and related civil industries - A technology foresight exercise to support further EU policy developments*, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/005929, JRC134926.

Table of contents

Abstract

The report presents the findings of a participatory technology foresight exercise that listed 46 emerging and disruptive technologies relevant for space, defence, and related civil industries, which are of strategic importance for the European Union (EU).

Throughout the process, participants focused on four future critical technologies that deserve particular attention: (i) quantum communications and cryptography; (ii) space platform; (iii) integrated photonics; and (iv) nuclear micro-reactors. These future critical technologies bear a high level of impact and a high probability of future EU dependency on others. For each one, the report includes a series of recommendations to address risks, challenges and future dependencies.

Beyond the listing and analysis of key technologies, the authors summarised 10 clusters of topics related to technology development and adoption: (i) geopolitics; (ii) cooperation; (iii) investment; (iv) market; (v) skills and knowledge; (vi) ethical issues; (vii) regulations and standards; (viii) development of technology building blocks; (ix) twin transition and security of assets; and (x) data and communications.

These insights can support further research and policy developments. The report concludes with a detailed explanation of the methodology applied and the results of intermediary phases.

Acknowledgments

The authors of this report would like to thank all experts that participated in the surveys, workshops and interviews held throughout this process. The time they dedicated to the process and the intellectual generosity they showed through their active and insightful contributions is very much appreciated.

The authors acknowledge and thank in particular Gert Runde, on his role as an external expert throughout the process, for the valuable guidance and support provided.

Executive summary

The report presents the findings from a participatory technology foresight exercise that was conducted between September and December 2022. It built on the participation of approximately 20 experts, coming from inside and outside of the European institutions, and representing several types of stakeholders. The foresight process used in this exercise was the result of a tailor made combination of several known methods, namely desk research, horizon scanning, sense making workshops, surveys and interviews.

The purpose of this exercise was two-fold: (i) to identify cross-cutting (relevant for space, defence, civil) emerging technologies that could be of strategic importance for the EU in the future; and (ii)_to identify priority areas that could reduce or avoid the development or emergence of existing or new dependencies.

The report assesses four potential future critical technologies:

- quantum communications and cryptography (including post-quantum cryptography);
- space platform (providing critical in-orbit services and operations);
- integrated photonics;
- nuclear micro-reactors.

The experts participating in the foresight exercise perceived these technologies as critical in the next 5+ years for the EU, meaning that they could have a high impact in space, defence and related civil industries. They could also present a potential risk of the EU's over-dependency on other countries.

Beyond identifying these future critical technologies, the foresight process also highlighted the risks and challenges associated with these technologies. For example, access to raw materials and components, access to a skilled workforce, regulatory and standardisation environment. Proposals for action were also harvested during the exercise that aim to mitigate those issues and bring opportunities further for the EU. These include: supporting start-ups; strengthening manufacturing capacities; promoting education and training; and retaining and attracting talent.

1 Introduction

Foresight is a discipline which aims at anticipating future developments by exploring trends, emerging issues and the potential challenges and opportunities accompanying them. Through the use of participatory methods and collective intelligence, it draws useful insights for strategic planning, policymaking and preparedness (European Commission, 2020). Its sub-discipline, technology foresight, covers a broad range of technologies and analyses the applications and diffusion of technologies including the societal context of technology applications (Rader & Porter, 2008).

Figure 1 - The European Union Flag

Source: Alexey Larionov on Unsplash

The Joint Research Centre (JRC) EU Policy Lab conducted a technology foresight process consisting of a series of foresight exercises. These exercises were carried out in the second half of 2022 in collaboration with the JRC Unit on Strategic Autonomy for Space and Security. Through exploratory, future-oriented and participatory exercises, foresight helped to identify:

- cross-sectoral (relevant for space, defence, civil) emerging technologies, which could be of a strategic importance for the EU in the future; and

— priority areas that could reduce or avoid the development or emergence of existing or new dependencies.

The Competence Centre on Foresight, an integral part of the EU Policy Lab, supports EU policy-making by providing strategic and future-oriented input, developing an anticipatory culture inside the European Commission, continuously experimenting and developing different methods and tools to make foresight practically useful for decision-making processes.(1)

The process comprised a combination of several known methods, namely desk research, horizon scanning (2), two sense making workshops (each one lasting two half-days), two small scale targeted surveys and interviews with JRC experts. This participatory process involved a wide range of experts coming from both inside and outside the European institutions, representing diverse policy and business domains and technology fields of expertise (see Annex for detailed description of the applied methodology). It aimed at highlighting the emerging technologies, which could have significant impact on the space, defence and civil industries (see Section 2), key drivers and enabling conditions, opportunities and challenges related to their development and adoption (see Section 2.1) and future critical technologies for the EU in a time span of 5+ years (see Section 3). The results could serve as useful insights for further detailed analysis over the next few years given the growing importance of establishing synergies between space, defence and civil industries in the EU, as foreseen in the action plan set up for that aim (European Commission, 2021).

It is important to recall that the nature of this foresight exercise is qualitative and participatory. Consequently, the outcomes described in the report do not present a (deterministic) forecast based on quantitative or statistical analysis, but rather identify and explore future developments and issues perceived as important for the future by this specific set of participants. Therefore it is the first step that should both support and be enriched by further research. It is also important to acknowledge that the work developed for this report does not capture all policy initiatives that are underway, inside and outside of the EU. In the same way, as the desk research and the participatory workshops took place in 2022, recent developments on both the technological and policy making side, might have been not considered, or can be already addressing some of the issues touched by the participants.

Finally, the authors consider that the methodology, developed for this specific work, is in itself a contribution for further analogous foresight exercises.

---

(1) https://policy-lab.ec.europa.eu/index_en

(2) Horizon scanning is a foresight method aimed at the early discovery of developments whose potential may not yet be widely recognized by most experts, decision-makers, or the general public. This method focuses on monitoring the margins of current thinking, research and innovation for novelties and phenomena that may offer distinct opportunities or challenges in the medium- or long-term time horizon. (Amanatidou, et al., 2012)

2 Emerging and disruptive technologies relevant to space, defence and related civil industries

The first phase of the foresight exercise consisted of desk research (see Annex 1 on methodology and intermediary outputs) of emerging and disruptive technologies in space, defence and related civil industries, and a horizon scanning that consisted of a collection of signals and a participatory workshop. Participants prioritised a number of emerging technologies that are relevant for at least two out of three domains (space, defence and related civil industries). Emerging technologies were perceived as having a significant impact in the future. Discussion and prioritisation were organised around four main groups of technologies. The results are set out in Table 1.

Figure 2 – 2022 State of the European Union (SOTEU) speech delivered by the President of the European Commission Ursula von der Leyen.

Source: European Parliament on Flickr

Some of the groups focused on capabilities because participants saw them as being equally important. Given the current fast pace of innovation, which is defined by increasing combinations of different technologies and innovative applications of already existing technologies, prioritising and clustering technologies is a hard task. In view of this, we mainly focused on exploring which technologies - and their innovative combinations – could generate future added value for defence, space and related civil industries, taking into account the underlying concepts of dual-use and cross-fertilisation between those sectors.

Table 1 - Preliminary prioritisation of technologies and capabilities within four clusters

— Novel components and materials, manufacturing and energy
● Nuclear micro-reactors
● 3D/4D printing in combination with AI and big data and advanced analytics
● New materials and/or innovations in energy storage and transport, including novel battery chemistries
● Recycling/substitution of critical raw materials / devices
● Integrated photonics
● Application-Specific Integrated Circuits (ASIC) / Field Programmable Gate Arrays (FPGA) / embedded FPGA design
● Gallium nitride (GaN) power electronics including packaging
— Digital and connectivity
● Cognitive computing continuum for better resource management
● Quantum communications and cryptography, including post-quantum cryptography
● Dependable AI – technically robust and respecting laws, standards and regulations
● Cloud-fog-edge computing continuum
● Edge AI, including cyber security of edge AI devices
● Cognitive digital twin
● Quantum sensing, including assured precision, navigation and timing
● Broadband connectivity in 6G
● Frugal (low-cost and easy deployable) AI
● Underwater real time communications
● Cognitive computing continuum for better resource management
● Quantum communications and cryptography, including post-quantum cryptography
● Dependable AI – technically robust and respecting laws, standards and regulations
● Cloud-fog-edge computing continuum
● Edge AI, including cyber security of edge AI devices
● Cognitive digital twin
● Quantum sensing, including assured precision, navigation and timing
● Broadband connectivity in 6G
● Frugal (low-cost and easy deployable) AI
● Underwater real time communications

— Mobility, autonomous systems and human performance enhancement
● Xenobots, neurobots, and other bio-hybrid molecular and nano-bots
● Exoskeletons and protective skin
● Directed energy (DE) technology
● Hypersonic vehicles
● Internet of the body things (IoBT)
● Multidomain swarming (Space, Air, Water, Ground)
● Brain-computer interfaces (BCI) and Augmented / Virtual reality (AR/VR)
● Unmanned Ground Vehicles (UGV)
● Bio-sensors and bio-informatics
● Miniaturised communications and sensor systems
● Electromagnetic shielding
— Space
● Reusable vehicles and components, including plug and play architectures
● Manufacturing SpaceVerse and In-space assembly manufacturing (ISAM)
● In-orbit servicing (IOS) platforms, Active debris removal (ADR) and End of life (EOL) services
● Space surveillance
● Space based solar power and power networks
● Lightweight radiation resistant materials for deep space human exploration
● Scaled-up, low-cost manufacturing of nano-systems and materials for space
● New designs for heat shields, sensors and other sub-systems
● Low temperature electronics and semiconductor technologies for 'natural' in-space operation and quantum computers
● Radiation hardened electronics
● Frequency hopping or Direct sequence code division multiple access (CDMA)
● Satellite security – protection from cyberattacks, high-powered lasers, and electronic warfare
● Emerging high-precision geodesy
● On board AI-based data processing
● Nuclear thermal-propulsion
● Satellite swarms
● Internet of space things (IoST)
● Sustainable fuels and launch cycles

Source: Authors, based on workshop discussion

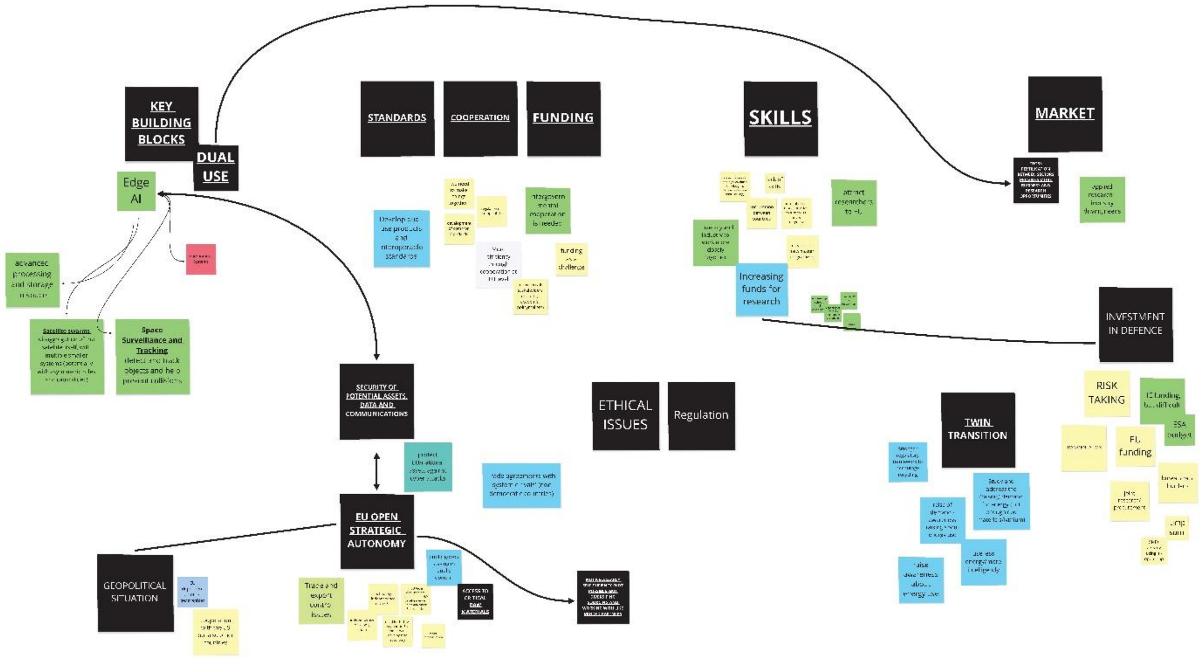
2.1 Drivers, enabling conditions, opportunities and challenges

This first phase of the foresight exercise helped to identify not only the emerging and critical technologies relevant to space, defence and civil sectors, but also the key drivers and enabling conditions, opportunities and challenges related to their development and adoption. The result is a set of common and cross-cutting topics, relevant to almost all emerging and disruptive technologies. This overarching approach is particularly useful to gain a global contextual snapshot, identify trends and trace potential stepping-stones for future policies and strategies. The 10 most pressing groups of topics, highlighted by the participants, are the following:

- Geopolitics: the EU's overdependence on other countries (especially non-democratic and not like-minded countries) in innovation, components and supply of raw materials will continue to be an issue that drives the need for further policies and mechanisms to support the development of an autonomous EU industry. The EU’s goal should be to develop an open strategic autonomy on key capabilities, reinforce cooperation with other countries where possible and build independent supply chains to protect public goods and critical knowhow from systemic rivals.
- Cooperation: cooperation is needed not only with like-minded countries and organisations, but also within the EU and across sectors (public, private and academia). There are areas where more joint procurement could be instrumental for critical technologies’ development.
- Investment: further coordination between public funding instruments is needed, both at the EU Member State and at the EU level. Investment in defence-related technologies needs to adopt a more risk-taking approach, following the mind-set of venture capital and dynamic startup innovation.
- Market: cross-fertilisation between sectors of key dual-use technologies represent an opportunity for funding, considering multiple business and research opportunities, and increasing the application domains of those technologies. To develop critical technologies, it is important to obtain further funding for applied research, where industry determines mostly the needs and priorities.
- Skills and knowledge: the lack of highly qualified experts in innovative technologies could become critical at a worldwide level. There is increasing competition between countries (including between EU Member States) and it is vital for the EU to train, retain and attract, technology specialists, researchers and other profiles related to innovation and legal experts specialised in technology.
- Ethical issues: the EU applies a distinct human-centric approach to technology development and adoption. Some technologies, including dual-use ones such as AI, autonomous systems and biotechnology, raise ethical issues. R&I activities and their applications need to be in line with European values and principles.

- Regulations and standards: interoperable solutions and the development of common standards bring confidence and contribute to R&I and market efficiency. The EU needs to anticipate and identify technologies for future standardisation, which will be important for its strategic positioning.
- Development of technology building blocks: technologies such as Edge AI are key building blocks for the future development of many other larger technologies and capabilities. The number of patent applications by European organisations systematically lags behind those of China and the US. This challenges the EU's ambition of becoming a technology leader.
- Twin transition: the rising demand for energy and raw materials will continue to drive the development of new green and digital technologies and innovations and the use of fewer resources.
- Security: security of assets, data and communications will be crucial to ensuring the EU's and its Member States' sovereignty and key intellectual property rights.

Figure 3 – Virtual board representing the results of the brainstorming exercise on common drivers, enabling conditions, opportunities and challenges across a set of emerging and disruptive technologies



Source: Authors based on workshop discussion. Visualisation: Miro online whiteboard, RealTimeBoard Inc., www.miro.com

3 Potentially critical technologies in 5+ years

3.1 Introduction

The second phase of the foresight exercise consisted in prioritising the initial list of emerging and disruptive technologies, presented in Section 2, in terms of future risks and challenges that could lead to EU over dependency in the future. The process included a participatory workshop, targeted interviews with JRC experts and a follow up survey, giving the opportunity to all participants to anonymously express their opinion after the workshop, but also to gather additional insights.

To define what a critical technology is, we referred to the definition provided in the action plan on synergies between civil, defence and space industries. The action plan states that:

'Critical technologies are technologies that are relevant across the defence, space and related civil industries and contribute to Europe's technological sovereignty by reducing risks of overdependence on others for things we need the most.' (European Commission, 2021).

Subsequently, we asked participants about their thoughts on technologies and their applications which in 5+ years: i) could have a high impact on at least two domains among the space, defence and related civil industries and ii) for which the EU may be at risk of overdependence. The terms "dependence" and "overdependence" were often used interchangeably given that in the context of open strategic autonomy, the EU will be open to trade and multilateral cooperation while promoting stable rules in order to be strong economically and have geopolitical influence. Here we define open strategic autonomy as reducing one-sided dependencies in critical areas as well as strengthen its capacity to set and implement its own priorities (Cagnin, Muench, Scapolo, Stoermer, & Vesnic Alujevic, 2021).

The outcome of the participatory process suggested four future critical technologies:

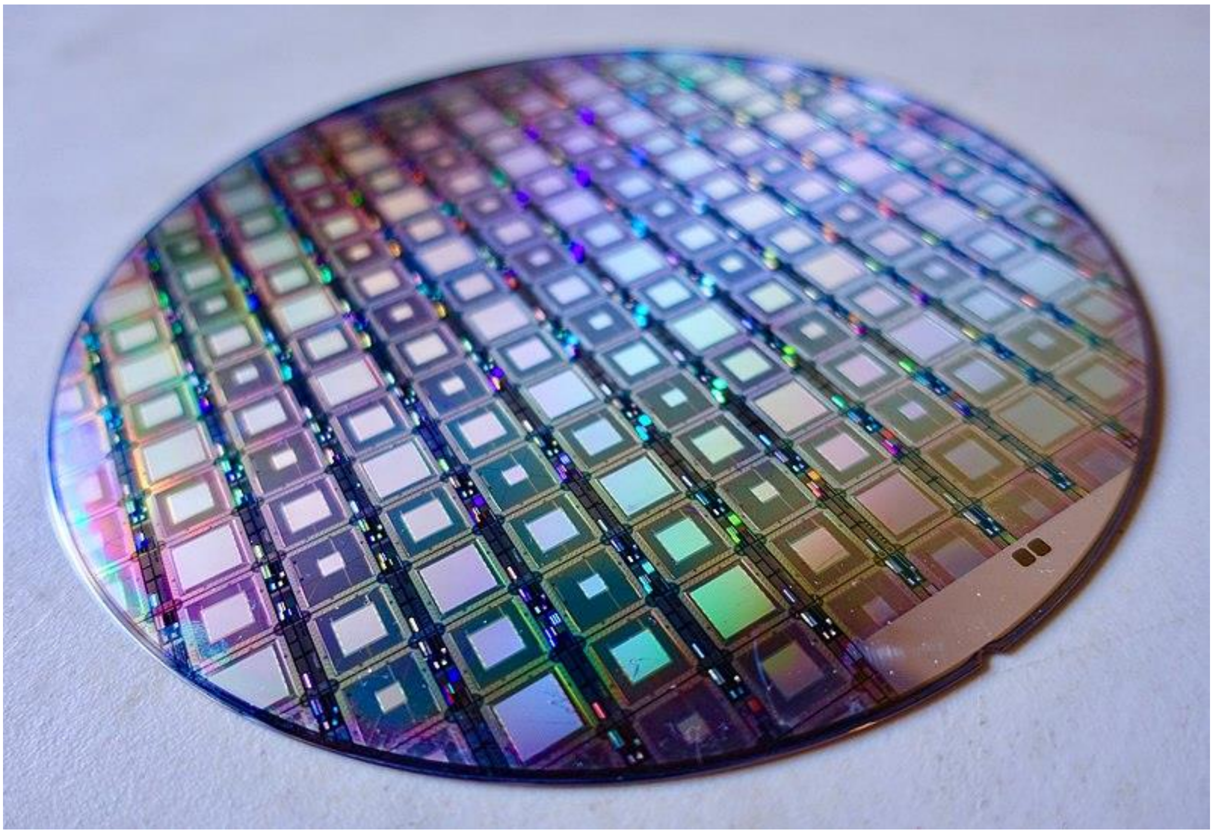
- Quantum communications and cryptography, including post-quantum cryptography.
- Nuclear micro-reactors.
- Integrated photonics.
- Space Platform – providing critical in-orbit services and operations.

Each of these technologies need to undergo more detailed and profound analysis in the future. Nevertheless, useful insights and indications for further actions are given in this section. For each of the four technologies, we report participants' assessment about: i) the main technology elements; ii) future evolution and application in the space, defence and civil sectors: iii) the risks, challenges and dependencies the EU may face in the future; and iv) the actions that could mitigate them.

3.2 Quantum communications and cryptography, including post-quantum cryptography

Quantum technologies are based on quantum physics and the interaction of molecules, atoms, photons and electrons. Technologies that we are currently using, such as MRI scanners for medical imaging, lasers, solar cells, electron microscopes, atomic clocks used for GPS and many others, are already relying on quantum effects, which however need limited control (3). Achieving full control over individual quantum systems would allow new capabilities for computation, digital communication, cryptography, sensing and imaging and others. Quantum communication, in particular, includes technologies and applications that aim to provide the most secure and trusted communication impossible to intercept without detection (4).

Figure 4 - A wafer of the latest D-Wave quantum computers



Source: Steve Jurvetson on Wikimedia Commons

3.2.1 Assessment

Participants highlighted the following core elements:

---

(3) https://uwaterloo.ca/institute-for-quantum-computing/quantum-101/quantum-applications-today
(4) https://qt.eu/discover-quantum/introduction-to-quantum-physics/

- Quantum key distribution, a method that allows securely exchanging a private encryption key between two parties. Any attempt at eavesdropping during the exchange of key will leave a trace that could be detected. Also, the extent to which the key was compromised could be measured (Lewis & Travagnin, 2018).
- Randomness is essential for quantum key distribution and quantum random number generator can produce random numbers that are unpredictable because of the inherently indeterministic quantum processes (5).
- Due to the intrinsic security of quantum information, it cannot be amplified through conventional repeaters. Quantum repeaters are being investigated to extend the range along which quantum information can be transmitted (Lewis & Travagnin, 2022). The building blocks are a quantum processor and a quantum interface to convert the information into photons (6).
- Single-photon detectors are used in quantum communication applications as many quantum cryptography protocols require single photons travelling over a channel.
- Photonic integrated circuits are very important for quantum technologies as they make devices and systems more robust, compact and cheaper (7).
- Quantum software and quantum optimised algorithms.
- Platforms and modular systems.
- Laser technology: quantum signals are transmitted by lasers in optical fibres.
- Laser communication in space: using laser communication in open space allows obtaining lower level of losses than in fibre communication and therefore an increased range to reach. As a consequence, satellites would have a major role in quantum communication infrastructures (8).

Secure communication that are difficult to intercept, trusted interactions and information exchange are of particular importance for critical infrastructures, but also for defence and military application. In addition, quantum technologies would significantly improve data collection, processing and exploitation capabilities, through networking together of quantum sensors and computers. Other areas that would benefit from these technology advancements include self-driving vehicles, financial transactions, cloud services, banking, health records and AI.

There is progress in enhancing system performance by developing more efficient quantum devices, such as single photon emitters, single photon detectors, low-noise detectors, modulators, sources of

---

(5) https://qrange.eu/faq/what-are-qrng

(6) https://qt.eu/discover-quantum/quantum-technologies-in-a-nutshell/

(7) https://qt.eu/discover-quantum/applications-of-qt/quantum-communication/

(8) http://www.qtspace.eu/?q=whitepaper

entangled photons, quantum random number generators, and quantum repeaters (9).

Another important development is satellite relayed quantum communication. This is a domain in which China is very active and has already launched two quantum-encrypting satellites, representing a major step towards a fully secured global communication network (10).

The EU’s long-term vision is the development of the Quantum Internet all over Europe: quantum computers, simulators and sensors interconnected via quantum networks distributing information and quantum resources (11). The technical milestones of the European Commission’s R&I initiative 'Quantum Flagship' envisages (12): in 3 years, development and certification of devices, systems protocols for quantum random number generators, quantum key distribution, quantum repeaters, quantum memories and long distance communication; in 6 years, cost-effective and scalable devices and systems for inter-city and intra-city networks as well as demonstration of scalable solutions for quantum networks connecting devices and systems, e.g. quantum sensors or processors; in 10 years, development of autonomous metro-area, long distance (> 1000km) and entanglement-based networks, a 'quantum Internet', as well as protocols exploiting the novel properties that quantum communication offers. The European Quantum Communication Infrastructure (EuroQCI) Initiative will make use of the quantum communication technologies developed by the Quantum Flagship. The European Commission, the European Space Agency and the EU-27 aim to build a secure quantum communication infrastructure that will span the whole EU, including its overseas territories, by 2027.

3.2.2 Risks, challenges and future dependencies

The main issues perceived as risks, challenges and dependencies that the EU may face in a time horizon of 5+ years are presented in 9 pre-defined groups.

Table 2 - Risks, challenges and future dependencies for quantum communication and cryptography

— Materials
● Materials for production of entangled photons and in particular:
● Nitrogen-vacancy (NV) centre in diamond
● Quantum dot materials
— Education, talent and skilled workforce

---

(9) https://qt.eu/discover-quantum/quantum-technologies-in-a-nutshell/
(10) https://spectrum.ieee.org/satellite-qkd-china
(11) https://digital-strategy.ec.europa.eu/en/library/quantum-flagship-major-boost-european-quantum-research
(12) https://qt.eu/discover-quantum/quantum-technologies-in-a-nutshell/

● Very high interest in quantum technologies would create shortage of experts.
— Components
● Single photon detectors
● Integrated photonics
● Safe algorithms
— Patents
● Low share of EU patents in worldwide patenting
— Logistics
● No particular issues were raised regarding logistics
— Investment
● Risk of uncoordinated EU investment initiatives
● Insufficient venture capital investment in the EU, particularly in comparison with the US
— Research, development & innovation
● Risk of lack of cooperation with non-EU European countries, such as Switzerland and the UK, which are strong in quantum technologies
— Regulation and standardisation
● Risk for EU losing influence in the international standard setting. Interoperability considerations would be critical for the successful application of quantum enabled devices and systems
— Other
● Challenge with respect to the decision whether to include quantum communications technologies in the EU export control list

Source: Authors, based on workshop discussion and interviews

The main risks and challenges for the future relate to the lack of talent and skilled workforce as well as low venture capital in the EU, particularly compared to the US. Low EU share in worldwide patenting and the EU's weaker position in international standard setting are also perceived, though to a lesser extent, as issues that could pose future risks for the EU.

Some further observations about factors influencing the future development and application of quantum communication technologies were made in the responses to the survey. These were: insufficient private investment for the development of quantum internet, the need to adapt the technology currently developed for NV centres to different platforms, lack of an agreed interoperable quantum network architecture and topology across all EU Member States, risk of technology hype cycle and inflated expectations, lack of adoption of quantum key distribution by relevant end users, public and private (including in industrial protocols).

3.2.3 Actions

Participants suggested the following actions in order to address the risks, challenges and dependencies highlighted above. Actions are organised around eight groups of issues and can address more than one challenge.

Table 3 - Mitigation actions proposed for quantum communication and cryptography

— Materials
• Improve EU capacity for processing while assuring high quality and purity, of highly specialised materials needed for quantum communication technologies
— Education, talent and skilled workforce
• Strengthen quantum technology education and training in the EU. Continue efforts done via the Quantum Flagship (13)
— Components
• Secure supply chain for single photon detectors based on avalanche photo diodes, for which EU system integrators depend on US and Japanese producers
— Patents
• Improve EU patent activity
— Investment
• Promote synergies between EU investment initiatives
• Support EU start-ups
— Research, development & innovation
• Seek cooperation with European countries, such as Switzerland and the UK
— Regulation and standardisation
• Strengthen EU role in international standardisation

Source: Authors, based on workshop discussion and interviews

Further comments gathered through the survey suggested several mitigation actions: i) explore alternatives of NV-centers ii) target investment on quantum communication among the various quantum technologies iii) agree on a EU-wide interoperable quantum network architecture and topology iv) work towards an EU masterplan covering quantum technology (i.e. QKD devices) but also operations and networking v) build up network operator capabilities and skills vi) work towards an easy integration with traditional cybersecurity mechanisms vii) inform about advantages offered by the application of quantum key distribution and clarify any uncertainties.

---

(13) https://qt.eu/

3.3 Nuclear micro-reactors

Nuclear micro-reactors are a subset of small modular reactors (SMRs) with a capacity below 10 MWe. Distinctive features are continuous operation and refuelling cycle between 10 to 30 years, capacity to operate autonomously, even when recovering from a malfunction and designed to be transported by road, rail, barge or air. They are principally intended for off-grid operation in remote locations (OECD NEA, 2023).

Figure 5 - Computer generated images of the Westinghouse eVinci nuclear micro-reactor representing the installation on a remote site and the easy transportable modular elements

Source: Westinghouse Electric Company

3.3.1 Assessment

Important elements highlighted by participants were:

- Generation IV nuclear reactor designs offering improved sustainability, safety, reliability and cost;
- Alternative nuclear fuels: high-assay low-enriched uranium (HALEU), Thorium, Triso;
- New materials resistant to corrosion and high temperature;
- Improved thermal-hydraulic modelling;
- Autonomous operation;
- For space applications, materials capable of resisting space radiation for long period of time;
- Nuclear fuel recycling and reprocessing;

- Advanced additive manufacturing for producing components.

The ability of micro reactors to operate independently from the electric grid makes them particularly attractive for key assets and critical infrastructures, such as military and governmental installations, data centres or hospitals. The urgent deployment of electricity is also particularly relevant during natural disasters, civil emergencies or in war zones. They could be used for space exploration, as lunar surface power systems, nuclear propulsion systems (thermal and electric) or powering human settlements in space. For maritime transport, micro reactors could provide alternative propulsion to conventional engines, which could reduce CO2 emissions but also allow emergency electricity supply in coastal regions. For industrial processes, micro reactors could provide electricity and process heat in continuous operation during 20 years.

3.3.2 Risks, challenges and future dependencies

The main issues perceived as risks, challenges and dependencies that the EU may face in a time horizon of five or more years are presented in 8 predefined groups.

Table 4 - Risks, challenges and future dependencies for nuclear micro-reactors

— Materials
● Availability of suitable neutron poisons - Er and Gd
● Processing of raw materials
● Enrichment of Uranium: currently, high-assay low-enriched uranium (HALEU) fuel is not produced at a commercial scale in Nuclear Energy Agency (NEA) member countries and the material is downblended from American or Russian high enriched uranium (HEU) stocks. However, according to the United States Department of Energy, HEU stocks could be completely exhausted by 2030-2040 (18)
— Education, talent and skilled workforce
● There would be a strong need for nuclear engineers and scientists but also for skilled workforce with technical profiles such as maintenance, welding and others
● There would be a need for human resources with appropriate legal background and expertise within nuclear safety regulations
— Components
● A completely new supply chain need to be set-up, ensuring relevant factory-fabrication methods, capabilities and fuel production capacities
— Patents
● Risk of dependencies on foreign patents due to current lack of incentives for patenting
— Logistics
● Spent nuclear fuel management

● New container designs for interim storage of used fuel
● New packaging and transport solutions
— Investment
● The US Department of Defence, US Department of Energy as well as NASA are already investing in the development of small modular reactors and micro-reactors
● Lack of cost sharing mechanisms between public and private investment in the EU
● In 2021, the US government committed investing in Romania for engineering and design of small modular reactors (SMR) (14)
● Currently, there is no market interest in the EU and diverging interests, which could potentially lead to dependencies on US products already established on the European market
— Research, development & innovation
● Strong innovation activity in the US, academic but also many start-ups
● Need for experimental units and appropriate research infrastructure
— Regulation and standardisation
● Certification of new transport containers
● Harmonisation of codes and standards
● Future commercial deployment will depend on resolving issues, such as the types of micro reactors within the meaning of 'nuclear power plant', the interpretation and application of international and regional safety and liability conventions
● Long, expensive and heavy regulatory process in the EU

Source: Authors, based on workshop discussion and interviews

The main future risk and challenges emerging concern the availability of key experimental facilities (for example, hot cells, laboratories, test reactors), the lack of nuclear engineers and scientists, the comparatively higher public and private investment in the US than in the EU and the heavy EU regulatory process, particularly compared to the US.

Some additional observations were made about factors affecting the adoption of nuclear micro reactors in the EU in the future. Risk of technology hype effects leading to unrealistic expectations. It is perceived that there is no EU market for such technology and consequently there are limited number of available sites for its deployment. As an alternative, small modular reactors could be considered. Also, there is a lack of appropriate regulatory experience especially in countries that only recently have started operating nuclear power plants. And the current regulatory process is not adapted to the new business models implied by the technology. Finally, there is a lack of sufficient

---

(14) https://www.state.gov/united-states-takes-next-step-in-supporting-innovative-clean-nuclear-technology-in-europe/

data to show the business case for adopting the technology.

3.3.3 Actions

Participants suggested the following actions in order to address the risks, challenges and dependencies listed above. Actions are organised around the pre-defined groups of issues and can address more than one challenge. As the workshop methodology included the use of wild cards, some actions address both the need to mitigate specific risks that arise from highly impactful and highly improbable events or to develop systemic resilience to handle a diverse set of risks.

Table 5 - Mitigation actions proposed for nuclear micro-reactors

— Materials
● Diversify the supply
● Extract uranium from seawater
● Consolidate agreements with like-minded partners, for example, Canada and Australia
● Address the issues related to the use of nuclear fuel in space such as its potential long-term storage outside Earth
— Education, talent and skilled workforce
● Attract experts and skilled workforce by providing career opportunities and attractive employment conditions
● Develop a strategy to facilitate mobility between industries and enabling technologies' domains
— Research, development & innovation
● Support EU start-ups by long term power purchase agreements, cost-sharing mechanisms or by providing access to experimental units and needed research infrastructure
— Regulation and standardisation
● Reinforce the agile and innovative tools and capacities of European nuclear regulators
● Provide the right resources and tools for regulators to tackle nuclear innovation
● Update current regulations to take account of developments in nuclear micro-reactor technology
— Other
● Have a clear long-term EU strategy and policy
● Develop shared EU nuclear fuel recycling and reprocessing capabilities

Source: Authors, based on workshop discussion and interviews

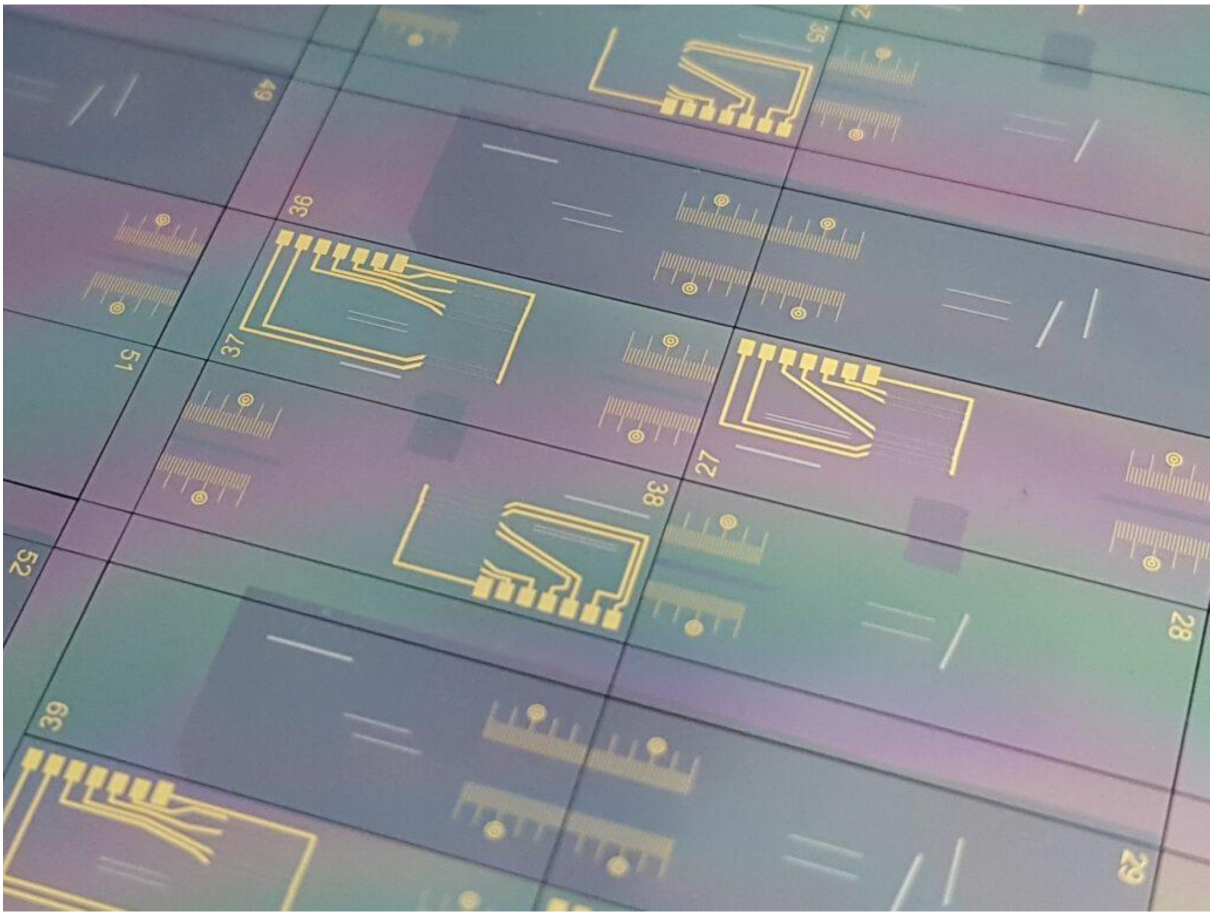
Additional comments provided through the survey proposed to strengthen EU collaboration within the Organisation for Economic Co-operation and Development (OECD) in this area and to strengthen the EU presence and influence in international organisations such as the International Atomic Energy

Agency (IAEA).

3.4 Integrated photonics

Integrated photonics is an emerging field of technology where photonics is used instead of electronics (15) and multiple photonic functions are integrated on a photonic integrated circuit. It is defined as 'an emerging branch of photonics in which waveguides and devices are fabricated as an integrated structure onto the surface of a flat substrate, or flat surface. As a result of integration, complex photonic circuits can now process and transmit light in similar ways to how electronic integrated circuits process and transmit electronic signals' (16).

Figure 6 - Silicon nitride photonic integrated circuit production



Source: [LioniX International]()

Integrated photonics is considered to have a considerable future application potential in multiple fields (17). Its application spans from telecommunication (e.g. 5G network), medicine (use of

---

(15) https://www.wevolver.com/article/an-introduction-to-integrated-photonics
(16) https://www.aimphotonics.com/what-is-integrated-photonics
(17) https://www.wevolver.com/article/an-introduction-to-integrated-photonics

biosensors in diagnosis) and automotive industry (use of LiDAR for detecting objects and distances as an important part of autonomous vehicles development) ([18],[19]) to sensing (for example, optical gas sensing (Hansel & Heck, 2020)). Another important potential application is for 'spectro-temporal transformations of quantum light pulses, which might lead to the future large-scale quantum network' (Zhu, Chen, Yu, & al., 2022). This was confirmed through the survey we conducted, stating that 'integrated photonics is one of the key enabling technologies not only for optical communications, but also for quantum computing, sensing and communication.'

3.4.1 Assessment

The participants of our workshop highlighted the following:

- Heterogeneous integration of materials: the workshop participants agreed that heterogeneous integration of materials on silicon is needed to further develop integrated photonics. Integrated nanoelectronics-photonics chips (including high-speed photonics interconnects) will be needed to reach full potential. Low-cost manufacturing processes would contribute to further development together with advanced cost-effective nanolithography and nanofabrication technologies in general.
- Potential applications: there are a number of potential applications for integrated photonics. For example, miniaturised sensing, high-efficient sensors for space environment monitoring (support for astronauts), quantum computing, neuromorphic computing (brain-electronic interfaces), quantum cryptography, broadband optical communications , (space) communication, secure communication, high-speed optical links.
- Strong R&D position: the EU currently has a strong R&D position and there is a need to stay on that path for the future. There are R&D efforts towards achieving large scale integration as well as towards integrated single-photon detectors and sources and CMOS-compatible electronic-photonic integration. However, while hybrid integration is well developed, monolithic integration needs further significant R&D efforts.
- High-performance communication: integrated photonics will be a critical technology for future high-performance communication. Therefore, it needs to remain as one of the EU's priorities. The lead in research needs to be capitalised industrially towards large-scale cost-effective manufacturing and new business models (for example, fab ([20])-less models).
- Space and Earth observation: one of the most promising future dual-use applications of integrated photonics is in space technologies and Earth observation, which will be

---

([18]) https://www.wevolver.com/article/an-introduction-to-integrated-photonics

([19]) https://www.imec-int.com/en/expertise/integrated-photonics/stay-ahead-imecs-latest-developments-integrated-photonics

([20]) In this context “Fab” refers to a fabrication plant, same as foundry.

increasingly used by the defence sector. Also, integrated photonics can support high-speed and very secure (encrypted) communication important for security and military applications. It could also increase data collection and processing for command, control, communications, computers, intelligence and surveillance. It will also affect server farms architecture due to the application of high-speed optical interconnects (replacing copper cable interconnects).

- Information availability: the strong impact on broadband communication could have positive influence on cheaper information availability, contributing to lower existing inequalities.

3.4.2 Risk, challenges and future dependencies

The main issues perceived as risks, challenges and dependencies that the EU may face in a time horizon of 5+ years are presented in 9 predefined groups.

Table 6 - Risks, challenges and future dependencies for integrated photonics

— Materials
● Raw materials' dependencies are similar to those for semiconductors. There are many materials used for their production and each needs to be analysed separately to determine possible existence of dependencies.
● Silicon, for example, is not critical for the moment but it is uncertain how this will develop in the future. The supply related to silicon might become critical if silicon photonics and hybrid integration (SoI and III-V compound semiconductors) become prevalent in manufacturing and the integrated photonics market.
● Due to long-term contracts in place for large industrial players, the availability of semiconductor materials in large quantities for start-ups might cause problems. While big industries have contracts for 50-100 years, start-ups, which might have patents, cannot enter the market because of problems in acquiring raw materials.
● Environmental issues might cause some shifts in the market and the increased price of raw materials in the future (e.g. gold). This could cause shifts in R&D priorities. According to the participants, for mining lithium, the EU needs to be a strong participant and governments need to invest more, also through assessing and securing environmental impacts despite the possible raise of costs. In this context, collateral industries might become important to create a circular economy in order to commercialise recycled materials.
— Education, talent and skilled workforce
● Education in photonics is not homogeneous across the EU though some European universities have good programmes in photonics. However, some experts fear that the EU might face lack of talent (e.g. engineers) and/or difficulties in keeping them in the EU (USA and Canada might become more attractive) to keep innovation at high level in this area.
— Components
● The EU has a big dependency in terms of manufacturing and packaging. In addition, in space and defence, component volume is small which could pose a problem in access to manufacturing. Packaging cost is very high and there might be strong dependencies from Far East foundries. This might become an issue especially if fabless models are implemented. Therefore, setting up manufacturing within the EU should be a priority.

— Patents
● The current patent situation in this area is not assessed as negative, while future situation will depend on availability of talent and R&D funding. Patenting will become more important for quantum and space applications, especially protecting the intellectual property (IP) in the manufacturing and design processes of the integrated circuit. Manufacturing capabilities have strong dependencies on the availability of very sophisticated manufacturing tools. Many leaders in this field are in the USA and Japan and developed a strong IP portfolio. When China will be able to manufacture those tools, this can become a game changer. Also, in some Asian countries trade secrets are used more than IP protection (e.g. patents) or publications, so monitoring IP and prior art might be complex.
— Logistics
● The supply chain in integrated photonics is very complex and involves many countries. A full EU supply chain would be ideal, or together with the 'trusted' partners. How to know/define which partners can be trusted is a more general question. If large-scale manufacturing is reached by the support of foundries in the Far East, logistics will become even more strategic. Problem with export control regimes might also emerge.
— Investment
● Working together with countries like China is likely to disappear. This could lead to decreased funding. Also, cheap production in non-EU countries could discourage investment in EU-based manufacturing. In the EU, there is no big foundry for photonic integrated circuit.
● Where to invest money is an important issue and especially how to encourage investment in environmentally friendly technologies that could potentially increase production costs.
— Research, development & innovation
● R&D depends largely on EU and other funding. Venture capital is required to stimulate SME creation. In this regard, there are many EU SMEs but they have difficulties to scale up.
● The bibliometric analysis shows that there is a growing number of publications in China and also Japan in this area. Furthermore, Japan has a strong first-mover innovation culture.
— Regulation and standardisation
● The production outside of the EU often lacks regulation. This could impact work conditions, environment, and fundamental rights. But, also, it could affect the reliability of photonic integrated circuit if manufacturing is done in non-EU foundries and there would be less control on this factor.
● When electronics-photonics integration reaches a very large scale, AI embedded at chip level and not recognised by the user might become a regulatory issue. Therefore, photonics integrated circuit for AI or other industries (led, automotive, etc.) will require regulation.
● Setting standards will be important for achieving technological sovereignty.
— Other
● Cheap manufacturing capabilities exist outside the EU. Paired with very high governmental incentives in China, this means that the EU will have difficulties to compete.
● Internalisation of external costs is another potential issue (but it applies to many other sectors too).
● High cost for sustaining the business operation could be also a challenge for the EU.

• Geopolitical evolution might also affect future dependencies.

Source: Authors, based on workshop discussion and interviews

3.4.3 Actions

The following actions have been proposed by the participants in order to address the challenges and bring opportunities for the EU:

Table 7 - Mitigation actions proposed for integrated photonics

— Materials
• Conduct technology foresight processes to assess better potential criticalities, including all materials in use, understanding levels of dependency and identifying how they can be mitigated
• Diversify sources in terms of supply
• Explore alternatives of the critical raw materials with diverse producers or manufacturing processes
— Education, talent and skilled workforce
• Incentivise the training of young researchers in integrated photonics through EU funded initiatives
• Continue promoting education in this domain equally across the EU
• Invest in training for young graduates
• Offer attractive career opportunities for the talents
• Train young researchers with a very pragmatic hands-on approach in research laboratories and manufacturing facilities
— Components
• Create advanced business models for component manufacturing, including a strategic EU vision in this area
— Patents
• Have more EU funded projects in integrated photonics
• Incentivise the projects to protect the IP through patents
• Assess what are priority vs other patents (where innovation originated and others for market and manufacturing reasons)
— Logistics
• Dismantle any obstacles for inward movement of talent (work visa, etc.)
— Investment
• Carefully govern investments from foreign financial operators through impact assessments. When big semiconductor manufacturing facilities (fabrication plants) proposed in certain

geographical areas, before granting authorisation, impact assessments are needed on economy, market, societal factors
● Invest and improve EU packaging (final circuit assembly) capacity
● Further invest into integration of photonics and electronics is needed
— Research, development & innovation
● Retain the expertise in the EU
● Maintain the EU funding in this area
● Support academic and industrial R&D, especially for costly equipment
— Regulation and standardisation
● Govern investments and conduct impact assessment of investment
● Deal with the takeovers of successful start-ups through regulation and IP management
● Create a strong IP portfolio: financial operations involving the acquisition of strong IP portfolios in integrated photonics should be carefully considered with a specific regulatory framework, as it affects the IP sovereignty and strategic EU independence

Source: Authors, based on workshop discussion and interviews

In the survey, an additional action was mentioned on the need to establish mutual relationships with suppliers/producers and develop new EU regulations or update current regulations to guarantee stability of these relationships.

3.5 Space platform – providing critical in-orbit services and operations

Workshop participants selected the deployment of a space platform (SP) as an enabling infrastructure to deliver in-orbit servicing (IOS) and operations, and as a critical capability to be developed by the EU.

IOS includes maintaining, repairing and decommissioning operations for space assets, and even if it is not a novel capability, its importance has been rising in recent years, due to the increasing deployment of satellites and constellations.

Space assets result from significant volumes of investment, and can continue to be useful after some critical resource have been exhausted or even if some key component or inherent technology has become obsolete (NASA, 2010). The concept of circularity applied to Space has gained attention over the last years. Beyond the critical function of reducing collision events, and extending life-time, studies have also pointed to the financially viability of In-orbit services due to the economic value of waste management and recycling (Leonard & Williams, 2023) (Saleh, Lamassoure, Hastings, & Newmand, 2003).

Therefore, it will be of significant importance to identify, develop and integrate the comprehensive set of technologies that the SP will require, in order to reduce the current (or risk of future) EU overdependence on others in this field.

3.5.1 Assessment

The following capabilities and technologies are key for the development of IOS and include some low technology readiness levels (TRL) items that could represent future critical technologies (FCT):

- Robotic arms and other solutions that enable manipulation capabilities needed in 'rendezvous', such as docking and grabbing.
- High-precision navigation, sensing and visualisation that are key to real time space surveillance and awareness (SSA) and again for the 'rendezvous' between two assets. Quantum sensing and imaging are FCT on this domain.
- AI can play several roles: 1) to support the operation of distributed space systems, such as swarms, that would be otherwise impossible to control (using humans only); 2) to provide autonomous operation capability, reducing the current high level of human intervention; and 3) for on-board processing (edge computing) that allows for a reduction in communications between the in-orbit and Earth.
- Satellite-to-satellite communications is crucial for servicing operations. In the future, quantum encryption will be a mainstream technology used in this context.
- The provision of materials that are resistant in space conditions, namely low-temperature electronics, radiation hardened electronics, thermal protection and radiation shielding for long-time permanence of humans in space (for which there is not yet a solution).
- Space propulsion, for which there is a current EU dependency, and re-entry systems.
- In-space manufacturing of components and fuel will take IOS to a next stage, by allowing maintenance and refuelling operations to becoming increasingly autonomous from Earth provisions.

IOS comprises a wide set of capabilities and applications. The SP will be a space asset that interacts with other objects in space, either through communication, monitoring, manoeuvring, docking (when necessary), protection from other space infrastructures or debris, but essentially intervening on other assets in operations such as: repairing, refuelling, de-commission (either by forcing re-entry or by recycling components), supporting construction (for instance for Earth-to-Moon missions). The SP is therefore important throughout the life cycle of those other assets.

Considering the underlying technologies, IOS can play a role in counter-space operations, such as inspect, follow, relocate and even disable competitors' assets. This latest domain has been for a long time, particularly relevant for state-to-state situations, but with the growing commercial exploration of space, the private sector will also play a critical role on delivering and on commissioning these services. On the other hand, dependence of states on private actors to deliver counter-space services is an issue that needs to be further discussed.

Beyond supporting communication and imaging satellites, the SP will be a key asset for several commercial business models and applications related with the exploration of space. In-space transportation (for Moon and Mars missions), exploration of space resources (such as asteroid mining) and energy generation and transportation will be dependent of a reliable and wide IOS infrastructure.

Despite the clear need for IOS and the critical role that the SP could play in supporting commercial uses of space (such as the very promising and profitable asteroid mining), participants agreed that there is still some lack of clarity on how IOS in itself could generate profit in the short to medium term. They foresee that in the next 10 years, there will be a need for a significant public investment, supported by EU and MS policies that will address the market gaps until businesses are fully sustainable.

Figure 7 - A space satellite hovering above the coastline

Source: SpaceX on Unsplash

Participants highlighted other development trends, related technologies and drivers:

- More autonomous operation, namely for servicing large fleets that will imply that humans will be less on the loop.
- Diversification of applications, connecting mechanisms, tools and technologies used.
- Possible consolidation of actors dependent on the success of business models, growth and dimensions achieved by those actors, and their funding source. We could see large actors acquiring smaller ones in order to integrate technology solutions and building blocks.
- Standardisation is key to facilitate interoperability between space assets, and we can expect advances in this field.

IOS is a dual use capability by nature considering that infrastructures such as the SP can service both civil and defence related assets. Beyond the commercial servicing, and as already mentioned, counter-space operations could be developed by the SP, namely surveillance of other objects but also neutralising and bringing down satellites. With its kinetic in orbit capability, the SP could also be easily weaponised, namely because it can put an object in collision route with others.

3.5.2 Risks, challenges and future dependencies

During the second workshop, participants identified 24 risks, challenges and dependencies among 9 predefined groups of issues. The follow up survey gave an indication which ones could contribute more for the future criticality of In-orbit servicing. The following list summarises the main insights gathered through this process:

Table 8 - Risks, challenges and future dependencies for space platform providing critical in-orbit services and operations

— Materials
● The two materials highlighted as critical in the future were:
▪ Lithium
▪ Titanium
● Other materials identified as baring risks were:
▪ Carbon fibre composites
▪ Thermoset resins
▪ High strength aluminium alloys
— Education, talent and a skilled workforce
● Human resources with interdisciplinary profiles such as cybersecurity, robotics, artificial intelligence, machine learning, additive manufacturing or quantum technologies, and also legal advisors

- Components & technologies
    - The most risky issue among the 24 is a critical component for space assets and operations: reliable electronics able to operate in space environment (resistance to low temperature, radiations, vacuum, etc.)
    - In this group “In space manufacturing technologies”, including the “manufacturing of nanoelectronics” were also highlighted
    - Other issues raised by participants, include:
        - Commercial off-the-shelf (COTS) components
        - Precision manipulators
        - Sensors for computer vision
        - Integrated photonics
        - On-board AI and data processing
        - Access to quantum-based technologies. (e.g., sensing, communications and cryptography)
- Patents
    - This was not considered as a potential problem for in-orbit servicing
- Logistics
    - In this domain, two challenges were highlighted as the second more risky issue among the 24, namely:
        - Access to space
        - In-space propulsion
- Investment
    - EU companies relocating to the US will pose a challenge for further advancing European autonomy and economic relevance in space
- Research, development & innovation
    - R&D&I is an area that participants highlighted as of high importance for In-orbit servicing, and where the EU should invest today to build and reinforce its technological sovereignty
    - There is also a high entry barrier for SMEs due to lack of national and EU funding for developing industrial R&D&I lab and prototyping/manufacturing infrastructure related to up-stream space
    - Participants also pointed to the 'lack of partnerships between academia and industry' as a medium impact challenge
- Regulation and standardisation
    - This cluster of issues does not include those that are significantly high risk. Nevertheless, some topics were pointed out during the process:
        - Ethical and regulatory frameworks impeding innovation

▪ Standards and guidelines (dependence on and influence from the US)
▪ Outdated global regulatory framework for conduct in outer space and liability
— Other
● Limited choice of non-EU collaboration partners due to geopolitical tensions (for example, Russia)
● The need to develop 'space situational awareness' capabilities

Source: Authors, based on workshop discussion and interviews

To sum up, we should point out that the biggest risk and challenge for the future on In-orbit servicing is connected with the development of specific electronic components, suitable for operations in space (either the current on-Earth production of such components, but also in the future, their production in space). The need for more experts, as for other critical technologies, poses challenges to the EU in the domain of Space. Although it is an issue shared by other geographies, it could limit EU's capacity, from R&I to operations. The supply of critical raw materials such as Lithium and Titanium was also highlighted, as was the access to space for the deployment of assets, a domain where the EU is, already today, over-dependent on others. On the more business and economic dimension, the EU risks seeing its businesses move to the US, where private venture capital investment is more abundant. The need for more private investment in the space industry was also raised by some participants.

3.5.3 Actions

The following actions were proposed by participants to address the risks, challenges and dependencies mentioned before, and develop a stronger EU strategic autonomy on In-orbit services.

Actions are organised through 9 clusters of issues. They can address more than one challenge. As the workshop methodology included the use of wild cards (highly impactful and highly improbable events), some actions address the need to mitigate specific risks that arise from such events, but also aim to develop systemic resilience to handle a diverse set of risks.

Table 9 - Mitigation actions proposed for space platform providing critical in-orbit services and operations

— Materials
● Establish EU bodies or organisations to monitor this issue, namely supply chain challenges
● Look for alternative technologies to avoid dependency on some raw materials
— Education, talent and a skilled workforce
● Attract qualified workers from other sectors, namely from the automotive industry, where a large existing work force could be converted and trained to work in the space industry
● Develop more innovation-led education, namely higher engagement of students with industry

● Create a professional association that recognises workers in Space, increasing this sectors brand value, the feeling of belonging and its overall attractiveness
— Components & technologies
● Increase the number of EU Member States with manufacturing capacity for electronics capable of operating in space
— Patents
● Reduce the costs on intellectual property protection
— Logistics
● Develop technologies for faster and easier access to space
— Investment
● Encourage more risk taking when investing in space technologies and capabilities
● Increase the engagement between public sector (at EU and Member State level) and private sector (industries) in order to align strategic directions in terms of private and public investment
— Research, development & innovation
● Encourage the cross-fertilisation of outputs for EU-funded projects to other initiatives
● Develop more links across sectors and application domains
● Increase industry’s involvement with high-education and research organisations
● Develop funding programmes to boost excellence in research and innovation in space research, through programmes, such as the Marie Curie Actions (European Research Executive Agency)
— Regulation and standardisation
● Increase the EU’s participation and influence in this industry’s standard setting processes
— Other
● Establish and develop good international relations across the geopolitical dimension, to increase or reinforce partnerships

Source: Authors, based on workshop discussion and interviews

4 Conclusions and recommendations

The outcome of the participatory foresight exercise suggested 46 emerging technologies, which could have a disruptive impact for the space, defence and civil domain.

Among those, the following four were perceived by participants as potentially critical in the future:

- quantum communications and cryptography, including post-quantum cryptography;
- nuclear micro-reactors;
- integrated photonics; and
- space platform as an enabling infrastructure for the delivery of In-orbit servicing.

These 4 technology domains, represent different levels of granularity, in both the level of detail covered by this report and the use case applications that are foreseen. This is a result of, among other factors, the limitations of the methodology and the maturity level of these technologies.

There are several issues common across the four technologies, which were perceived as future risks and challenges that the EU may face. Those four challenges were assessed in more detail and relate to the lack of talent and skilled workforce, risk of a brain drain, the need to support EU start-ups and the importance for the EU to have an active role in standardisation.

It is also interesting to note the interconnection among these four technologies from both the perspective of their development and interdependency as well as the common risks and challenges they face. For example, integrated photonics will play a significant role for quantum communication technologies and the two of them will be needed for the development of in-orbit space services. Small nuclear devices are also explored for providing power for extended space exploration missions. (21) Consequently, acting upon the future risks of one of these technologies would have a beneficial effect on one or several of them.

From the point of view of dual use, all these technologies appear to have both civil and military related applications, which - as raised in the desk research and the workshops - is an opportunity to create synergies in terms of research and investment. But at the same, may subject them to EU rules on export control (22).

In terms of funding mechanisms, the EU already covers in some degree these four technology domains. Initiatives such as Horizon Europe (23), including its programmes like the European

---

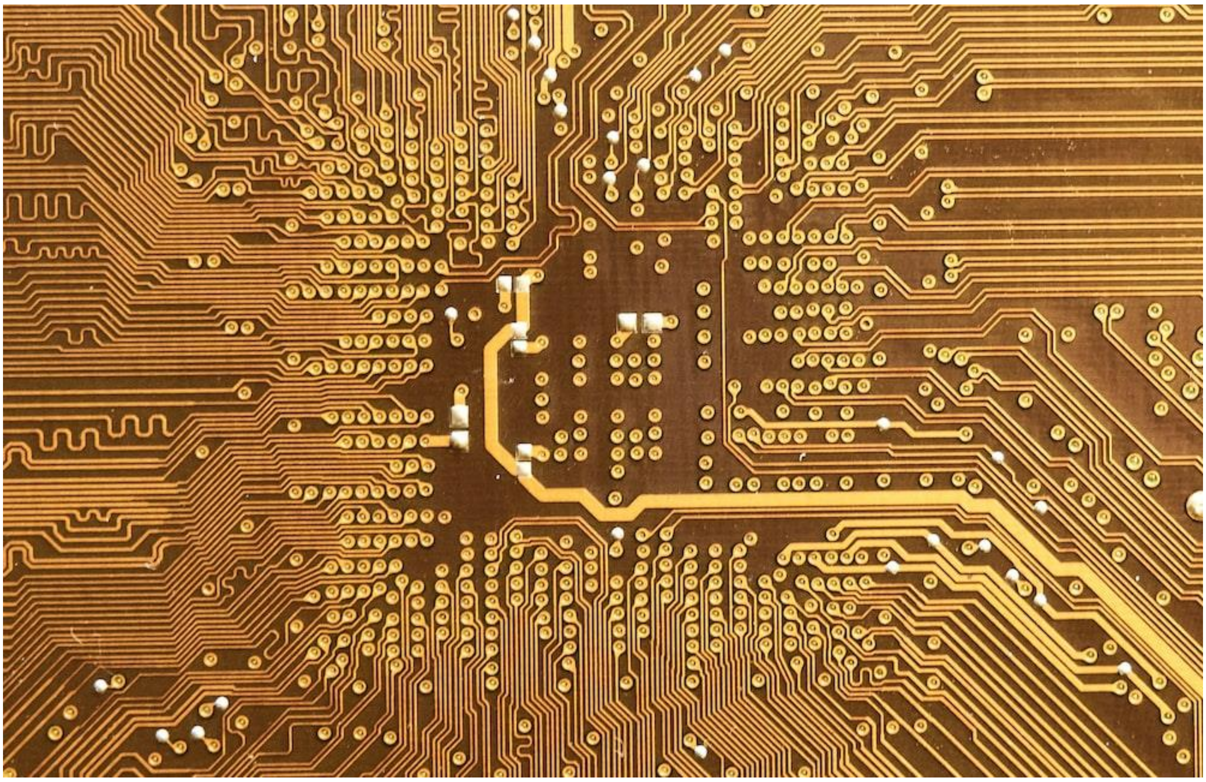
(21) Tanarro Colodron, J. and Freis, D., Nuclear power in space, Simola, K., Goulart De Medeiros, M. and Konings, R. editor(s), European Commission - Joint Research Centre, Petten, 2022, JRC131078

(22) Regulation (EU) 2021/821 of the European Parliament and of the Council of 20 May 2021 setting up a Union regime for the control of exports, brokering, technical assistance, transit and transfer of dual-use items.

(23) Horizon Europe (europa.eu)

Innovation Council ([24]), the European Partnerships ([25]), the Space Programme ([26]) and the Flagships ([27]), address funding needs across several technology readiness levels, and aim to bridge early-stage research to market and scaling-up. Nevertheless, the pace of technological breakthroughs, and development of novel applications and solutions of already known technologies, demand a systematic exercise of selection and priorisation of funding topics. And most especially a detailed analysis of funding needs and gaps that if addressed, could support researchers, businesses and industrial clusters to consolidate the European space and defence industrial ecosystems.

Figure 8 – An integrated circuit



Source: Manuel on Unsplash

Further detailed analysis is recommended to assess the full scope of the opportunities and challenges that this set of technologies bear. As well as the synergies that need to be explored between the space, defence and related civil industries, and identify what policies still need to be put in place to encourage the right R&I and business environment. This analysis includes (among others): supply chain analysis, technology roadmaps (when still needed) and risk assessments. As well as sustainability analysis, considering the global challenges related with the sourcing of raw materials and the lifecycle of equipment and infrastructures. Even if some cross-cutting issues are already

---

([24]) European Innovation Council (europa.eu)
([25]) European Partnerships in Horizon Europe (europa.eu)
([26]) Space Programme (europa.eu)
([27]) Flagships | Shaping Europe’s digital future (europa.eu)

highlighted in this conclusion, the authors consider that further steps should focus on deepen the knowledge on these cross-cutting issues and include a multi-criteria analysis.

It is important to note that this foresight exercise does not present a deterministic forecast, but is based on a qualitative and participatory process, which helps identifying and exploring possible upcoming developments and issues perceived as important for the future.

Annex 1

Description of the foresight methodology applied and intermediary results

1 Introduction

This document describes the specific foresight methodology applied for the development of the technology foresight activity. Technology foresight (TF) covers a broad range of technologies and analyses the applications and diffusion of technology including the societal context of technology applications (Rader & Porter, 2008).

This exercise aimed to highlight what are the future critical technologies for EU in a time span of 5+ years. By future critical technologies in this context we mean, technologies and their applications that bear simultaneously a) a future risk of overdependence of the EU on others and b) a high impact on the fields of space, defence and related civil industries. These emergent and potentially disruptive technologies are crucial to keep the role of the EU as a world leader in several economic sectors.

The TF process developed and applied specifically for this exercise comprises a combination of several known methodologies, namely desk research, horizon scanning, sense making workshops, small scale targeted surveys and interviews with experts. This participatory process involved experts coming from both inside and outside the European institutions, representing several policy and business domains and technology fields of expertise.

Through the literature review and the workshops, we tried to cover space, defence and related civil industries from different perspectives, including the military and security side and the commercialisation and industrialisation of space, as well as the issue of dual use technologies (for example, technologies that may be applied both in civil and military domains).

The outputs of this TF process present a low to medium level of granularity on what concerns the definition of technologies and the drivers and enabling conditions that encourage their development. The objective of this TF process was not to provide a comprehensive assessment of what these technologies are and could be, but to raise the emergent opportunities and challenges they carry, some of them probably below the radar of most policy makers, so they could be later on researched and assessed in detail. It is, therefore, an exploratory work developed to support technology foresight activities, namely by highlighting some of the technologies that should be the focus of further detailed analysis during the upcoming years.

2 Process

The foresight process applied in this case was a combination of several foresight methods that complemented each other. The aim was to capture different sources and perspectives and to triangulate and validate the outputs produced by the different methods.

The process, including 7 stages, is summarised in Figure 9 and described in more detail in sections 3 to 9 of this annex.

Figure 9 - Foresight process developed and applied for technology foresight activities in 2022

Source: Authors

3 Desk research

Objectives

The objectives of the desk research were:

- Identify drivers, enabling conditions, opportunities and challenges related with technology development & adoption in the areas of space, defence and related civil industries;
- Identify key disruptive and emergent technologies;
- Group technologies into clusters that could be used along the process.

Description

The first step was to identify what the relevant sources for this brief literature review should be. The selected sources focus on the military, security and space applications of technologies.

Sources include reports published by the European Commission's Joint Research Centre (JRC) and other organisations such as the North Atlantic Treaty Organisation (NATO), the European Defence Agency (EDA), the United States of America's Government, the RAND Corporation and the Royal United Services Institute (RUSI) from the United Kingdom. The authors can provide the research report and the complete list of sources upon request.

The research was divided in two mains steps and outputs. The first was to identify drivers, enabling conditions, opportunities and challenges related with technology development & adoption. A STEEP - Social, Technological, Economical, Environmental and (Geo) Political – framework was used to identify and group these issues. It is often difficult to classify drivers in a single dimension of STEEP and when approaching issues related with technology we mostly see strong connections between that driver and the others. Social, Economic, Environmental and (Geo) Political aspects, drive technology development strongly and the majority of the topics actually play in two or more of these dimensions. For that reason, an alternative grouping of drivers was used, using combinations of the STEEP dimensions.

Table 10 - Six combinations of the STEEP dimensions and 30 topics identified for the foresight exercise

— Social and technological
● Regulatory and ethical frameworks of emergent and disruptive technologies (EDA, 2021) (Moro, Vetere Arellano, Farulli, Hristova, & Krzysztofowicz, 2021) (Eulaerts, Joanny, & Fragkiskos, 2022) (Blumenthal, Hottes, Foran, & Lee, 2021)
● Organisational challenges resulting from the use of unmanned platforms in the battlefield (EDA, 2021)
● Human capital and the skills of the 21st century soldier (Moro, Vetere Arellano, Farulli, Hristova, & Krzysztofowicz, 2021) (NATO, 2020)
● Citizens expectations with digital inclusion and privacy protection (NATO, 2020)
— Social and environmental
● Evolving concept of security, extending beyond the military realm (EDA, 2021) (Moro, Vetere Arellano, Farulli, Hristova, & Krzysztofowicz, 2021)
● New roles for the military, including emergency and disaster management and dealing with non-controllable movements of the population (EDA, 2021)
— Social and (geo)political
● Support for common defence and security from EU citizens (European Commission, 2022)
● Changing nature of warfare, including increased mobility, indirect means and private actors (Kaushal, 2019) (EDA, 2021) (Moro, Vetere Arellano, Farulli, Hristova, & Krzysztofowicz, 2021)
● Citizens as intelligence providers and misinformation in an increasing hybridisation of conflicts (EDA, 2021)
— Technological and economic
● EU’s investment in R&I behind China and the US (Eulaerts, Joanny, & Fragkiskos, 2022)
● Increasing EU’s awareness and support for the development of critical technologies (European Commission, 2021)
● Increasing costs of defence and technology advantage (Barnes, 2019) (Moro, Vetere Arellano, Farulli, Hristova, & Krzysztofowicz, 2021)
● Public perception of defence and security funding (NATO, 2020)
● Data as an economic resource as important as water, food, energy and raw materials (NATO, 2020)
● Innovation networks and ecosystems joining industry, government and academia (NATO, 2020)
● Space becomes a contested, complex and democratised landscape with more state and private actors and new threats (Moro, Vetere Arellano, Farulli, Hristova, & Krzysztofowicz, 2021) (Black, Slapakova, & Martin, 2022) (EDA, 2021) (NATO, 2020) (Stickings, 2019)

● Wide range of space use cases connected with terrestrial and hybrid economic activities (Black, Slapakova, & Martin, 2022)
— Technological and (geo)political
● Future conflict operating environment shaped by several issues, such as situational awareness, electromagnetic spectrum and less command-and control architectures (Moro, Vetere Arellano, Farulli, Hristova, & Krzysztofowicz, 2021) (Bronk, 2019)
● Cyberspace consolidated as a battleground with the emergence of electronic warfare and the growing power of private actors (EDA, 2021)
● Technologies such as data science and automated decision-making have not delivered the expected or assumed decisive edge, showing the current limitations on the use of technology (Roberts, 2019)
● Russian investment in biotechnology sector with a key role from the private sector (Blumenthal, Hottes, Foran, & Lee, 2021)
● China access to health data causing security risks (Blumenthal, Hottes, Foran, & Lee, 2021)
● USA and China as quantum technologies' leaders (Parker, 2021)
● European technological sovereignty in the defence sector depending on further industrial development and integration (Moro, Vetere Arellano, Farulli, Hristova, & Krzysztofowicz, 2021)
● Control of space as the high ground, leads to the control of land and sea (Stickings, 2019)
— Economic and (geo)political
● Awareness about the importance of geopolitical cohesion and a common European defence policy (Moro, Vetere Arellano, Farulli, Hristova, & Krzysztofowicz, 2021)
● Cooperation is key to address funding challenges, through better institutional coordination and connecting the different financial sources and mechanisms (NATO, 2020)
● Synergies between civil security, defence and space industries are fundamental to reach critical mass (European Commission, 2021) (Moro, Vetere Arellano, Farulli, Hristova, & Krzysztofowicz, 2021)
● Disruption of international supply chains in the defence sector and emergency of new actors (Moro, Vetere Arellano, Farulli, Hristova, & Krzysztofowicz, 2021)
● New energy sources, critical resources and other economic drivers will lead to new domains of potential confrontation and types of conflict (EDA, 2021)

Source: Selection and clustering done by Authors using findings in the bibliographic references

The second step was to identify trends, strong and weak signals related to emerging, disruptive and critical technologies and innovations, in the context of space, defence and related civil industries. These concepts (emerging, disruptive and critical) were not used as interchangeable, but as part of the wide range of relevant classifications for this work. In the same sense, the range was extended to include both technologies (including enabling technologies and materials) and innovations (as products of an innovative combination or applications of technologies that might not be new themselves). These technologies manifest themselves through trends and signals that present several grades of manifestation, consolidation and novelty. All of these were considered.

The insights were clustered in six main groups, and a series of sub-groups as shown in Table 11.

Table 11 - Main groups and sub-groups for clustering desk research insights

— Digital & connectivity
● Cybersecurity
● Advanced computing
● Quantum enabled technologies
● Artificial intelligence
● Disinformation & misinformation
● Data
● Connectivity
● Systems
— Mobility & weapons
● General trends
● Unmanned military systems
● New types of weapons
— Space
● General trends
● Emerging technologies
● Defence
● Operations and energy
— Human performance enhancement
● General trends
● Bio and gene engineering
● Internet of the body (IoB), prosthetics and exoskeletons
— Novel components and materials & manufacturing
● Components and devices
● Novel materials and manufacturing
● Semiconductors and microelectronics
— Energy
● General trends
● Energy storage

Source: Clustering done by Authors using findings in the following bibliographic references: (NATO, 2020) (Moro, Vetere Arellano, Farulli, Hristova, & Krzysztofowicz, 2021) (Eulaerts, Joanny, & Fragkiskos, 2022) (Blumenthal, Hottes, Foran, & Lee, 2021) (Parker, 2021) (EDA, 2021) (Black, Slapakova, & Martin, 2022) (National Science and Technology Council, 2022) (NATO Science & Technology Organization, 2020) (Roberts et al., 2019).

The number of signals in each one of these groups is different, due to the fact that some domains are emergent and still do not bear a significant number of use cases. Nevertheless, it was important to highlight the main fields where we can foresee future developments in research, innovation and technology adoption.

Outputs

A report containing a summary of the insights collected through the desk research, was produced and shared in advance with the participants of Workshop 1 (step 3 of the foresight process), as a complementary source of signals. The authors can provide the research report and the complete list of sources upon request.

This report also helped the foresight team to build a basic understanding on what are the most pressing issues and the most relevant technologies in the scope of the space, defence and related civil industries. This was important to design and run the workshops with experts, as it allowed the team to better facilitate the discussions.

4 Horizon scanning

Objectives

Scan for signals and trends on emerging and disruptive technologies and innovations.

Description:

Horizon scanning is a foresight methodology aimed at the early discovery of developments or events not yet on the radar of most experts, decision-makers, or the general public. It is not a predictive tool, but rather a qualitative exploration of possible future novelties still at the margins of mainstream knowledge, and it helps to think about the directions of such novelties, their current uncertainties, potential configurations, plausible impacts, and more. It can reveal blind spots in the collective knowledge and expose us to what to expect from what we do not know that we do not know, our unknown unknowns. It allows us to better anticipate tomorrow’s changes or disruptions through the assessment of specific signals.

When applied in technology foresight, it aims to identify signals related with emerging and disruptive technologies, innovations and connected issues, such as drivers, enabling conditions, opportunities and challenges. And, in the context of this exercise, signals related specifically with the use of dual use technologies in space, defence and related civil industries.

For the participation in the horizon scanning, the 2 workshops and the 2 surveys of this project, the authors launched an invitation for participation to experts, coming from inside and outside of the European Institutions. The final group of about 20 participants, contained multiple profiles (from policy makers, businesses' representatives, associations' representatives, researchers from research and technology organisations, academia and consultants), all coming from relevant policy, scientific, technological or industrial domains.

Participants in Workshop 1 (see next point) were invited to submit such signals through a specifically designed webpage at the European Commission's website EUSurvey ([28]). With this request, a document with detailed information was sent, namely containing the definition of 'horizon scanning' and 'signal', and instructions about what each submission should include: a title, a brief description, a justification of the relevance and its source.

Outputs

About 60 signals were received and analysed. Signals that were found duplicated, incomplete or that did not relate with the purpose of the exercise were removed.

A total of 50 signals were then selected, compiled in a report and shared back with all the participants. The authors can provide the full list of horizon scanning items upon request.

Together with the desk research findings, signals were used to prepare Workshop 1 (see Point 5).

5 Workshop 1

Objectives

The first technology foresight workshop focused on emerging and disruptive technologies, main drivers, enabling conditions, opportunities and challenges in the research, development and application of technologies in the defence, space and related civil industries. It took place online on 26 and 27 September 2022.

This participatory workshop was part of the horizon scanning process. This sense-making session built on the desk research, the horizon scanning process and the expertise of the participants. Ahead of the workshops, participants were invited to submit, through an online tool, signals related to emerging and disruptive technologies for the horizon scanning process, as described in the previous point.

Process

Participants received 50 signals ahead of the workshop. These signals were clustered in four groups (see below). Considering the asymmetric number of signals in each of the six technology groups defined during the desk research, some of them were merged and renamed, as follows:

([28]) Launched in 2013, EUSurvey is the European Commission's official survey management tool. Its main purpose is to create official surveys of public opinion and forms for internal communication and staff management. https://ec.europa.eu/eusurvey/

- Digital and connectivity;
- Mobility, autonomous systems, weapons and human performance enhancement;
- Space; and
- Novel components and materials, and energy.

During the workshop, participants were asked to select and prioritise the most relevant signals through collaborative work and discuss challenges and opportunities. Day 1 focused on prioritising the 50 signals and adding new ones if needed. Day 2 focused on discussing challenges and opportunities for users, policymakers and businesses for selected technologies.

Outputs

As mentioned above, the discussion and prioritisation were organised around four main groups of technologies and results are presented in table 12. Some of the output relates to capabilities as participants perceived them as equally important.

Table 12 - Prioritised list of emerging and disruptive technologies

— Digital & connectivity
● Cognitive computing continuum for better resource management
● Quantum communications and cryptography, including post-quantum cryptography, precision navigation and timing
● Dependable AI – technically robust and respecting laws, standards and regulations
● Cloud-fog-edge computing continuum
● Edge AI, including cyber security of edge AI devices
● Cognitive digital twin
● Quantum sensing, including assured precision, navigation and timing
● Broadband connectivity in 6G
● Frugal (low-cost and easy deployable) AI
● Underwater real time communications
— Novel components and materials, manufacturing and energy
● Nuclear micro-reactors
● 3D/4D printing in combination with AI and big data and advanced analytics
● New materials and/or innovations in energy storage and transport, including novel battery chemistries
● Recycling / substitution of critical raw materials / devices
● Integrated photonics

● Application-Specific Integrated Circuits (ASIC) / Field Programmable Gate Arrays (FPGA) / embedded FPGA design
● Gallium nitride (GaN) power electronics, including packaging
— Mobility, autonomous systems and human performance enhancement
● Xenobots, neurobots, and other bio-hybrid molecular and nano-bots
● Exoskeletons and protective skin
● Directed Energy (DE) technology
● Hypersonic vehicles
● Internet of the body things (IoBT)
● Multidomain swarming (Space, Air, Water, Ground)
● Brain-computer interfaces (BCI) and Augmented / Virtual reality (AR/VR)
● Unmanned ground vehicles (UGV)
● Bio-sensors and bio-informatics
● Miniaturised communications and sensor systems
● Electromagnetic shielding
— Space
● Reusable vehicles and components, including plug and play architectures
● Manufacturing SpaceVerse and In-space assembly manufacturing (ISAM)
● In-orbit servicing (IOS) platforms, Active debris removal (ADR) and End-of-life (EOL) services
● Space surveillance
● Space based solar power and power networks
● Lightweight radiation resistant materials for deep space human exploration
● Scaled-up, low-cost manufacturing of nano-systems and materials for space
● New designs for heat shields, sensors and other sub-systems
● Low temperature electronics and semiconductor technologies for 'natural' in-space operation and quantum computers
● Radiation hardened electronics
● Frequency hopping or Direct sequence code division multiple access (CDMA)
● Satellite security – protection from cyberattacks, high-powered lasers, and electronic warfare
● Emerging high-precision geodesy
● On-board AI-based data processing
● Nuclear thermal-propulsion

● Satellite swarms
● Internet of space things (IoST)
● Sustainable fuels and launch cycles

Source: Authors.

6 Survey 1

Objectives

The objective of the first survey was to assess the emerging and disruptive technologies identified during Workshop 1 in terms of their future impact and risk of future EU overdependence on others. The purpose was to produce a shortlist of future critical technologies, assess which of them should be further analysed in Workshop 2 and in which domains there could be a higher criticality.

Description

The survey was developed to provide additional insights for Workshop 2 (next step 5 in the foresight process), based on the results of workshop 1 (previous step 3 of the process). Considering the scope of the overall foresight exercise and the number of respondents (low and limited to only some of the participants) the results cannot be considered fully representative, and the findings should be analysed carefully. Nevertheless, this was a useful step to feed the experts' discussions and should be considered as part of the qualitative method of the sense making workshops.

Beside the initial questions on the profile of participants, there were four sections of questions, one for each of the four technology fields used in Workshop 1, namely:

- Digital and connectivity;
- Mobility, autonomous systems, weapons and human performance enhancement;
- Space; and
- Novel components and materials, and energy.

In each section, participants graded the listed capabilities, technologies and innovations according to their:

- level of future impact in space, defence and related civil Industries, in a time horizon of 5+ years, through a scale of 1 (low impact) to 5 (high impact);
- risk of future EU overdependence on others in a time horizon of 5+ years, through a scale of 1 (low risk) to 5 (high risk).

In each section participants also:

- selected one of the capabilities, technologies and innovations that was top graded in the previous answer on dependency, to be assessed in more detail.

- Having the previous answer in mind, assessed the level of future EU dependency, through a scale of 1 (low dependency) to 5 (high dependency), in the following domains:
  - Critical raw materials supply;
  - Education, talent and skilled workforce;
  - Components;
  - Patents;
  - Logistics;
  - Investment;
  - Research, development & innovation; and
  - Regulation and standardisation.

Outputs

As mentioned before, these survey results have to be analysed carefully. Even if they confirmed some of the insights gathered during the conversations held in Workshop 1 and were later validated by experts during Workshop 2, the low number of responses limits their representativeness.

Capabilities, technologies and innovations were ordered through a rating formula that took into account the average level of future impact, the average risk of future EU overdependence and the number of votes. The formula is the following:

rating = "impact" x “overdependence” x ((“votes”+1) x 50%)

The list of top voted items is the following:

- Quantum communications and cryptography, including post-quantum cryptography;
- Nuclear micro-reactors;
- Multidomain swarming (Space, Air, Water, Ground);
- Miniaturised communications and sensor systems;
- Integrated photonics;
- New materials and/or innovations in energy storage and transport, including novel battery chemistries;
- Space surveillance;
- Quantum sensing, including assured precision, navigation and timing;
- Radiation hardened electronics;
- In-orbit servicing (IOS) platforms, Active debris removal (ADR) and End-of-life (EOL) services; and
- Broadband connectivity in 6G.

From these items, participants were invited to select which critical technologies should be assessed in more detail during Workshop 2 and later be mentioned in the final report, as explained in the next step.

7 Workshop 2

The second workshop tool place online on 25 and 26 October 2022.

The objectives were to explore future critical technologies and use results of survey 1 (previous step in the foresight process) to go more in-depth into particular technologies and explore the potential future dependencies, risks, challenges and opportunities.

The results from the previous Workshop 1, as well as from the survey were used as starting point. Participants were asked to look at the results and agree on the technology they consider the most critical for the future. Four technologies were identified as the most critical for the future of the EU:

- Quantum computing;
- Integrated photonics;
- Nuclear micro-reactors; and
- Space platform for in-orbit servicing.

The results of this workshop are described in more detail in Section 3 of the main report.

8 Additional interviews

Based on the output of Workshop 2, additional interviews were conducted to refine and validate the results of the workshop with in-house experts from the European Commission Joint Research Centre and other Directorates-General. They were asked to assess and elaborate on the same issues that were discussed in the workshop. These interviews helped us better understand the topic and dive deeper into certain areas of dependencies, risks and challenges related to four technologies discussed above. The results of the interviews have been merged with the overall results of the workshop and survey.

9 Survey 2

Objectives

The objectives of the survey was to evaluate and quantify risks highlighted in the previous workshop and to collect additional proposals of actions to address risks.

Description

As for the previous one, Survey 2 was developed to provide additional insights following Workshop 2 and was carried out through EUSurvey with all responses being anonymous.

Considering the scope of the overall foresight exercise and the relatively low number of respondents, despite their expertise in these fields, the findings should be analysed with caution. Nevertheless, it was a useful step to highlight and validate some of the insights that participants produced during Workshop 2.

Beside the initial questions regarding the participants' profile, there were four sections of questions addressing each one of the four critical technologies that were selected and assessed by participants in Workshop 2:

- Quantum communications and cryptography;
- Nuclear micro-reactors;
- Integrated photonic; and
- In-orbit servicing.

Inside each section participants:

- Selected, from a previous list, the group of issues in which the EU should invest today to build and reinforce its technological sovereignty. The groups, previously used in Survey 1 and Workshop 2 are as follows:
    - Critical raw materials supply;
    - Education, talent and skilled workforce;
    - Components;
    - Patents;
    - Logistics;
    - Investment;
    - Research, development & innovation; and
    - Regulation and standardisation.
- Graded a list of future risks and challenges the EU may face in a time horizon of 5+ years. This list was developed in Workshop 2 and is specific for each one of the four technologies. Risks were rated from 1 (low impact) to 5 (high impact).
- Provided additional risks and challenges not envisaged in the previous list.
- Suggested actions the EU should put in place to address one or more of risks mentioned in the previous answers.

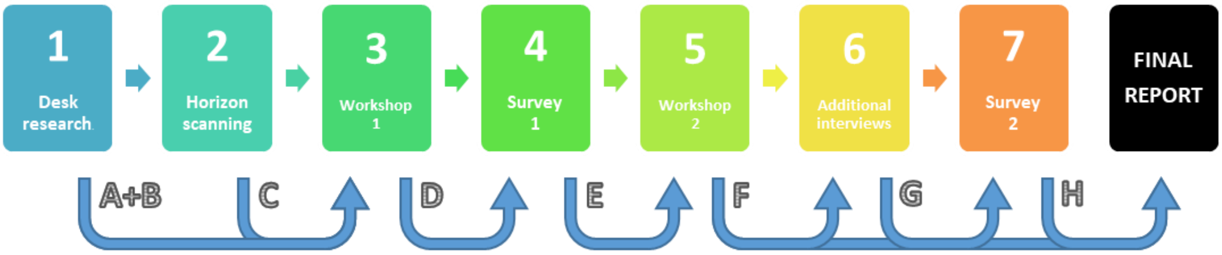
Outputs

The outputs of the survey are not sufficiently representative due to the low number of responses received. Nevertheless, they provide important hints on which risks and challenges should be the focus of closer attention, and therefore some of the insights were included.

10 Final remarks and lessons-learned

As descried in this annex, this was an iterative process, where each step produced outputs that feed into subsequent phases. The knowledge management and the intermediate results are summarise in figure 10.

Figure 10 - Summary of the knowledge management and intermediate outputs of the process.



A 6 combinations of the STEEP dimensions and 30 topics containing drivers, enabling conditions, opportunities and challenges related with technology development & adoption. Proposed by the authors following desk research (Table 10).

B 5 groups of technologies and subgroups proposed by the authors following desk research (Table 11).

C 50 signals containing relevant technologies and technology applications, submitted by the participants.

D 46 emerging and disruptive technologies selected by the participants and clustered in 4 groups (Table 12)

E Assessment by the participants of the 46 emerging and disruptive technologies in terms of their future impact and risk of future EU overdependence on others. Rating of technologies done by the authors (see formula in section 6 of the annex)

F 4 future critical technologies, selected by the participants. Assessment of each technology considering: risks, challenges and future dependencies across 9 topics. (tables 2, 4, 6 and 8). Potential action proposals to address risks, challenges and dependencies (tables 3, 5, 7 and 9)

G Complementary information provided by selected JRC experts.

H Complementary information provided by participants.

Source: Authors.

The technology foresight methodology applied in this exercise was decisive to reach the proposed objectives. Through a multi-stakeholder and participatory process, it delivered a short list of future critical technologies across different fields of applications within the scope of the space, defence and related civil industries. It has also supported a high-level assessment of eventual risks, challenges and dependencies surrounding those critical technologies and raised potential actions to address them. The applied foresight approach started with the identification of a significant amount of information on signals and trends surrounding technologies in space, defence and related civil industries, and throughout the consecutive steps of sense making, clustering and prioritisation, ended up in a summarised list of critical technologies and related issues.

These findings are therefore a product of the collective intelligence created through a participatory process with a particular group of experts and should be complemented by other sources. It provides a high-level analysis of technologies that are still emergent and not completely well known. They bear a certain level of uncertainty and their detailed features and future developments should be assessed and monitored further on. As stated in the introduction, the main objective of this foresight process was to support ongoing and future policy making processes and open up the discussion about different possible future developments and not to forecast how exactly the future will look like.

In terms of lessons-learned, several opportunities for improvements were identified throughout this foresight process. These are an important considerations to take into account for similar technology foresight exercises:

- Scope
  - Scoping, defining the objectives and the expected outputs and outcomes of a foresight exercise, especially in the context of a larger assessment work, is of crucial importance. Technology foresight enables a better understanding of the complexity and the possibilities of future technology developments and applications. Therefore, it does not aim to produce deterministic conclusions, but rather to scan the horizon, make sense of information and raise possible developments, in order to anticipate better and shape future policies. It is a distinct exercise from assessing current technologies, namely their applications, manufacturing and supply chain issues.
  - Having this in mind, there is a margin to explore and improve how these two functions connect and complement each other, namely how foresight outputs could inspire further future-oriented technology assessments.
  - It is also important to understand how foresight could further support eventual policy initiatives that arise in the context of the action plan on synergies between civil, defence and space industries. This would help to further shape the process and its outputs in order to better meet the needs of policymakers.
- Experts
  - The efficiency of participatory methods is linked with the level of engagement that is established with participants, ways of harvesting their knowledge and what they perceive to gain from participating.
  - In technology, foresight processes there is an additional challenge regarding the need to engage highly qualified experts, usually over a wide scope of technology fields and representing different types of stakeholders. Therefore, there is a limited number of potential participants that meet these criteria, and the ones that do so, often have limited time to engage with such exercises.
  - On the other hand, the networking dimension, the opportunity to contribute individually to high level policy making processes and keeping up with the latest developments on their field, are some of the key motivational dimensions that stakeholders value, when engaging in such processes.
  - The establishment of expert panels and/or communities organised according to technology groups and/or domains of application could be a solution to improve expert engagement. Participants could interact periodically in these forums, and when needed, they could be quickly invited to provide insights for the foresight process, namely through horizon scanning, workshops, surveys and interviews.
- Workshops
  - Technologies, such as video-conferencing and collaborative digital canvas provide us today, especially since the COVID-19 pandemic, with valuable tools to support online collaborative processes, that otherwise would be challenging in terms of logistics, time and cost.
  - Organising online collaborative workshops, where experts meet virtually to discuss pressing topics following a predefined method, has become the most common option. This allowed organisations, such as the European Commission, to continue to engage internally and externally

even with travelling and meeting restrictions, and to do so in a quick and easy way, and participants to spend less time travelling and organising their trips.

- Nevertheless, the use of online tools and processes, even if bearing some level of efficiency, does not replace completely in-person sessions. Empirical experience shows us that in offline sessions participants get more committed to the process, and the quality and number of insights generated in such sessions is higher when compared with online ones. Therefore, in future exercises it would be advisable to mix both formats.

Bibliography

Amanatidou, E., Butter, M., Carabias, V., Könnölä, T., Leis, M., Saritas, O., . . . van Rij, V. (2012). On concepts and methods in horizon scanning: Lessons from initiating policy dialogues on emerging issues. *Science and Public Policy 39*, 208-221. doi:10.1093/scipol/scs017

Barnes, P. (2019). *The Future Conflict Operating Environment Out to 2030 - The West: A Unified Concept of War?* Royal United Services Institute for Defence and Security Studies. Retrieved from https://static.rusi.org/201906_op_future_operating_enviroment_web.pdf

Black, J., Slapakova, L., & Martin, K. (2022). *Future Uses of Space Out to 2050 - Emerging threats and opportunities for the UK National Space Strategy.* Santa Monica, California and Cambridge, UK: RAND Corporation. doi:10.7249/RRA609-1

Blumenthal, M., Hottes, A., Foran, C., & Lee, M. (2021). *Technological Approaches to Human Performance Enhancement.* Santa Monica, California: RAND Corporation. doi:10.7249/RRA1482-2

Bronk, J. (2019). *The Future Conflict Operating Environment Out to 2030 - Technological Trends.* Royal United Services Institute for Defence and Security Studies. Retrieved from https://static.rusi.org/201906_op_future_operating_enviroment_web.pdf

Cagnin, C., Muench, S., Scapolo, F., Stoermer, E., & Vesnic Alujevic, L. (2021). *Shaping and securing the EU`s Open Strategic Autonomy by 2040 and beyond.* Luxemburg: Publications Office of the European Union. doi:10.2760/727114

EDA. (2021). *EDA Technology Foresight Exercise 2021 - Methodology.* European Defence Agency. Retrieved from https://eda.europa.eu/docs/default-source/documents/eda-technology-foresight-exercise-(2021)---methodology88ffba3fa4d264cfa776ff000087ef0f.pdf

Eulaerts, O., Joanny, G., & Fragkiskos, S. (2022). *Weak signals in Science and Technologies - Weak signals in 2021: technologies at a very early stage of development that could impact the future.* Luxembourg: Publications Office of the European Union. doi:10.2760/700257

European Commission. (2020). *Strategic Foresight*. Retrieved from https://commission.europa.eu/strategy-and-policy/strategic-planning/strategic-foresight_en

European Commission. (2021). *Action Plan on Synergies between civil, defence and space industries.* Brussels: European Commission. Retrieved from https://commission.europa.eu/system/files/2021-03/action_plan_on_synergies_en_1.pdf

European Commission. (2022). *Eurobarometer: Europeans set defence and energy autonomy as key.* European Commission. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/ip_22_3756

Hansel, A., & Heck, M. (2020). Opportunities for photonic integrated circuits in optical gas sensors. *Journal of Physics: Photonics, Volume 2, Number 1*. doi:10.1088/2515-7647/ab6742

Kaushal, S. (2019). *The Future Conflict Operating Environment Out to 2030 - Politics and Demographics in the 21st Centuary: Networks and Neo-Feudalism?* Royal United Services

Institute for Defence and Security Studies. Retrieved from https://static.rusi.org/201906_op_future_operating_enviroment_web.pdf

Leonard, R., & Williams, I. (2023). Viability of a circular economy for space debris. *International Journal of Integrated Waste Management Volume 155*, 19-28. doi:10.1016/j.wasman.2022.10.024

Lewis, A., & Travagnin, M. (2018). *The Impact of Quantum Technology on the EU's Policies Part 2 Quantum communications: from science to policies, EUR 29017.* Ispra: European Commission. doi:10.2760/881896

Lewis, A., & Travagnin, M. (2022). *A secure quantum communications infrastructure for Europe: technical background for a policy vision, EUR 31133.* Luxemburg: Publications Office of the European Union. doi:10.2760/180945

Moro, A., Vetere Arellano, A., Farulli, R., Hristova, M., & Krzysztofowicz, M. (2021). *Trends and drivers in the changing defence and security paradigm – JRC workshop, March 2021.* Ispra: European Commission.

NASA. (2010). *On-Orbit Satellite Servicing Study - Project Report.* Greenbelt: NASA - Goddard Space Flight Center. Retrieved from https://nexis.gsfc.nasa.gov/images/nasa_satellite%20servicing_project_report_0511.pdf

National Science and Technology Council. (2022). *Critical and emerging technologies - List update.* Office of Science and Technology Policy, United States Government. Retrieved from https://www.whitehouse.gov/wp-content/uploads/2022/02/02-2022-Critical-and-Emerging-Technologies-List-Update.pdf

NATO. (2020). *NATO Advisory Group on Emerging and Disruptive Technologies - Annual Report 2020.* Brussels. Retrieved from https://www.nato.int/nato_static_fl2014/assets/pdf/2021/3/pdf/210303-EDT-adv-grp-annual-report-2020.pdf

NATO Science & Technology Organization. (2020). *Science & Technology Trends 2020-2040 - Exploring the S&T Edge.* NATO Science & Technology Organization. Retrieved from https://www.nato.int/nato_static_fl2014/assets/pdf/2020/4/pdf/190422-ST_Tech_Trends_Report_2020-2040.pdf

OECD NEA. (2023). *Small Modular Reactors: Challenges and Opportunities.* Paris: OECD-NEA. Retrieved from https://www.oecd-nea.org/jcms/pl_57979/small-modular-reactors-challenges-and-opportunities?details=true

Parker, E. (2021). *Commercial and Military Applications and Timelines for Quantum Technology.* Santa Monica, California: RAND Corporation. doi:https://doi.org/10.7249/RRA1482-4

Rader, M., & Porter, A. (2008). Fitting Future-Oriented Technology Analysis Methods to Study Types. In *Future-oriented technology analysis: Strategic intelligence for an innovative economy* (pp. 25-40). Heidelberg: Springer-Verlag.

Roberts et al. (2019). *The Future Conflict Operating Environment Out to 2030.* Royal United Services Institute for Defence and Security Studies. Retrieved from https://static.rusi.org/201906_op_future_operating_enviroment_web.pdf

Roberts, P. (2019). *The Future Conflict Operating Environment Out to 2030 - Conclusions and deductions.* Royal United Services Institute for Defence and Security Studies. Retrieved from https://static.rusi.org/201906_op_future_operating_enviroment_web.pdf

Saleh, J., Lamassoure, E., Hastings, D., & Newmand, D. (2003). Flexibility and the value of on-orbit servicing: New customer-centric perspective. *Journal of Spacecraft and Rockets Volume 40*, 279-291. Retrieved from https://www.researchgate.net/publication/280055309_Flexibility_and_the_value_of_on-orbit_servicing_New_customer-centric_perspective

Stickings, A. (2019). *The Future Conflict Operating Environment Out to 2030 - Space, Strategic Advantage and Control of the Military High Ground.* Royal United Services Institute for Defence and Security Studies. Retrieved from https://static.rusi.org/201906_op_future_operating_enviroment_web.pdf

Zhu, D., Chen, C., Yu, M., & al., e. (2022). Spectral control of nonclassical light pulses using an integrated thin-film lithium niobate modulator. *Light Sci Appl 11*, 327. doi:10.1038/s41377-022-01029-7

List of figures

List of tables

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls)

— at the following standard number: +32 2 299 96 96

— via the following form: european-union.europa.eu/contact-eu/write-us_en.

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

Open data from the EU

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets

Publications Office
of the European Union