Australian Government
Department of Defence
Defence Science and
Technology Organisation

Future Technology Themes: 2030 to 2060

Nik Luketic

Joint and Operations Analysis Division
Defence Science and Technology Organisation

DSTO-TR-2877

ABSTRACT

In support of Air 07/036, DSTO seeks to explore new areas of technology that might be available over the next 20 to 50 years. There is a vast body of literature on the direction the developments in future technologies may take. Described here is a literature coding method that was developed for the purposes of this study. The method selects only sources that originate from expert views and applies a weighting scheme that aims to ensure the inclusion of independent and unique perspectives. The result is a diverse, ranked list of 100 future technologies appearing out to 2060 based on an analysis of the open literature. The report also includes a brief discussion of future environmental issues that form the context to the hypothesised technological developments. This technique developed here is suitable for conducting traceable and thorough literature reviews with limited analytical resources.

RELEASE LIMITATION

Approved for public release

Published by

Joint and Operations Analysis Division
DSTO Defence Science and Technology Organisation
506 Lorimer St
Fishermans Bend, Victoria 3207 Australia

Telephone: 1300 DEFENCE
Fax: (03) 9626 7999

© Commonwealth of Australia 2013

AR-015-680
July 2013

APPROVED FOR PUBLIC RELEASE

Future Technology Themes: 2030 to 2060

Executive Summary

As part of an ongoing task (Air 07/036) to support the future air and space capabilities for the Royal Australian Air Force (RAAF), the Air Force Headquarters (AFHQ) asked the Defence Science and Technology Organisation (DSTO) to examine the following question:

"What new areas of technology might be available in the 20-50 year timeframe that should influence how Air Force develops current and future forces?"

This report presents the results of a study in support of this task that canvassed the publicly available literature on environmental trends and technology forecasts. The data presented here will inform follow-on studies specifically concerned with the impacts of developments in technology on air power.

Presented here are reviews of environmental trend forecasts and possible technology developments. Consideration of technology trends is the main aim of this study and the environmental trends presented here are for providing the contextual background within which technologies will evolve. This part of the study considered only literature from large multi-expert panels.

The data relating to technology developments considered a much wider body of literature. A scoring and filtering scheme was developed here to manage the vast body of literature relating to anticipated future technologies. The aim of the process was to rank concepts according to their prevalence in the literature with the following constraints:

- ensure that only expert opinion is included,
- maximise the influence of culturally independent forecasts
- ensure that less mainstream ideas can still have visibility in the results.

The report has a detailed description of the rationale behind the method and its application.

The top and bottom five of the most persistent technologies are provided in Tables E-1 and E-2 respectively. The most persistent technologies reflect the prevailing, mainstream perspectives about what sort of future technologies we are likely to see out to 2060. These are characterised by technologies that span multiple application areas; and that are likely to see significant civilian and possibly military investments into their development. The least persistent technologies represent the least mainstream (the most unconventional)

perspectives about the shape of future technologies that exist at the periphery of current futures thinking – these are often unorthodox, domain-specific (such as space technologies); and mostly apply to niche applications areas (such as weapons or aerospace vehicles).

Table E-1 Five of the most persistent future technologies

Technology	Cross-disciplinary effects	Application and usage examples	Horizon
Nanomaterials and structures	All	Application of nanotechnology to embed multifunctional characteristics into materials.	2018-2030
Bio-mechanical robotic integration and biomimetic devices	Biological Augmentation; Aerodynamic configurations	Introduction of biomimetic implants[1] and biologically inspired mechanical concepts[2]. Remote control of insects in flight[3]. Development of bioelectronic devices[4]. Application of biomimetic robotics[5]. Autonomous decision making on robotic platforms[6]. Intelligence [sic] service robots[7].	2020-2035
Computational drug design and testing	Simulation	Modelling and mathematics to develop working models of complex biological processes for the identification of disease and prediction of DNA interactions. Nascent fields such as biosimulation, pharmacogenomics are expected to mature first and will give rise to fully predictive biomedicine for development of tailored treatments, including addiction. “Laptop labs” will allow the simulation of bio-processes in the early design of drugs[1, 4, 7, 8, 9]	2020-2060
Bio-factories and biological substrates	Materials; Manufacturing; Energy	Large scale manufacturing of synthetic biochemicals[10]. New discoveries of reproducible biological processes and molecules[11]. Mass application of artificial photosynthesis to organic solar cells (artificial leaves)[12]. DNA modification of animals and plants to produce new materials (spider silk spinning from goat milk)[13]. Use of silk worms to spin spider silk[14].	2020-2030
Artificial implants for improvements or recovery of biological functions, including brain-machine interfaces	Materials	Controlling/mimicking high-order biological functions through synthetic means[1,4]. Artificial extensions of human capabilities, including brain repair (2020-2030)[15]. Long lasting, bio-compatible cochlear, optoelectronic implants for better sensing performance[6]. Brain-machine interfaces[1,16,17].	2020-2030

Table E-2 Five of the least persistent future technologies

Technology	Cross-disciplinary effects	Application and usage examples	Horizon
Reusable Air breathing Access-to-Space Launch	Propulsion; Materials; Communications and sensing	Vertical takeoff space launch using rocket first stage and air breathing rocket-scramjet second stage. Requires advanced thermal materials, automation, onboard health monitoring systems[16].	2030
Rapidly Composable Small Satellites	Materials; AI; Communications and sensing	Modular components for fast insertion. Includes automatic recomposition should systems fail, communications via secure links. Cooperative control, guidance, on-orbit self-assembly. Attitude control, orbital manoeuvre, communications, ISR, weapons modules[16].	2030
Fractionated/Distributed Space Systems	Materials; AI; Communications and sensing	Provides redundancy, survivability and system upgradeability. Fractionation will involve system elements that cooperate and communicate via secure, jam-resistant links (laser). Such systems are easily added to/repaired by adding or substituting small satellites[16].	2030
Space-based lasers	Materials; Space; Fuel/Power sources	Two concepts: ground based laser with mirrored space relays or a space-based solid-state laser[18].	2030
Future airborne laser	Materials; Fuel/power sources	Aircraft mounted (nuclear-powered) laser on board a manned platform with extremely long endurance (crew-limited)[18].	2030+

Presented in the report are implications of the range of identified technologies and a set of narratives placing them in the contexts of possible environmental drivers.

The method developed here for filtering and scoring the literature gives the operations research (OR) practitioner an ability to quickly and systematically process a diverse set of data with the application of simple weightings that reflect the goals of the study.

---

[1] Silberglitt, R., et al. (2006) The Global Technology Revolution 2020, In-Depth Analyses Bio. *Nano/Materials/Information Trends, Drivers, Barriers, and Social Implications*

[2] United States Air Force (USAF) (2009) *United States Air Force Unmanned Aircraft Systems Flight Plan 2009–2047*. Washington, DC: Department of the Air Force.

[3] Bozkurt, A., GILMOUR, R. and Lal, A. (2009) Balloon-Assisted Flight of Radio-Controlled Insect Biobots. *IEEE transactions on biomedical engineering* **56** (9) 2305

[4] National Institute of Science and Technology Policy (NISTEP). *Overview of research*. Research on Science and Technology Foresight. (2004) [Accessed 2010 04/10/2010]; Available from: http://www.nistep.go.jp/nistep/about/thema/themaA-e.html.

[5] Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 302*. (2007) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/302/.

[6] NATO, Research and Technology Organisation (RTO) and TaskGroup062 (2010) *Assessment of Possible Disruptive Technologies for Defence and Security*. NATO Research and Technology Organisation (RTO)

[7] The State Council of China (2006) *Medium- and Long-term National Plan for Science and Technology Development 2006-2020.*

---

8 Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 461*. (2006) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/461/.

9 Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 283*. (2010) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/283/.

10 Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 417*. (2007) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/417/.

11 Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 530*. (2004) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/530/.

12 Koo, H. J., et al. (2010) Aqueous soft matter based photovoltaic devices. *J. Mater. Chem.*

13 Bushnell, D. M. (2001) Future Strategic Issues/Future Warfare [Circa 2025]. *EMERGING TECHNOLOGIES: Recommendations for Counter-Terrorism*

14 Teulé, F., et al. (2012) Silkworms transformed with chimeric silkworm/spider silk genes spin composite silk fibers with improved mechanical properties. *Proceedings of the National Academy of Sciences* **109** (3) 923-928

15 Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 438*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/438/.

16 Chief Scientist (AF/ST) USAF (2010) *Technology Horizons: A Vision for Air Force Science & Technology During 2010-2030*.

17 Ministry of Defence (MoD) (2006) *Defence Technology Strategy*.

18 Air University (US) Air Command and Staff College (2008) *Blue Horizons (BH) II 2008 Final Report*.

Author

Nik Luketic
Joint and Operations Analysis Division

Nik graduated from the University of New South Wales (Sydney) with a double degree in Aerospace Engineering (Hons.) and Physics in 2009. He joined DSTO (and former AOD) at the end of September 2010. Nik has since been employing his growing operations research skills while supporting the division's research in future technologies; RAAF experimentation activities; and the development of new helicopter tactics and operational concepts through qualitative research and simulation development.

This page is intentionally blank

Contents

LIST OF ACRONYMS

1. INTRODUCTION 1
  1.1 Approach 1

2. METHOD 3
  2.1 Study Assumptions 3
    2.1.1 Accuracy of forecasts 3
  2.2 Requirements Pull and Technology Push 4
    2.2.1 The literature on environmental trends and drivers 4
    2.2.2 The literature on emerging and future technologies 4
  2.3 Method for filtering the technology forecast literature 5
  2.4 Information Scoring 6

3. RESULTS 11
  3.1 Environmental Trends and Drivers 11
    3.1.1 Physical Environment 11
    3.1.2 Social Environment 13
    3.1.3 Economic Environment 14
    3.1.4 Security and Defence 15
  3.2 Emerging and Future Technologies 17
    3.2.1 Overview 17
    3.2.2 Persistent technologies 18
  3.3 Future Technologies Narrative 24
    3.3.1 Life Sciences 24
    3.3.2 Materials and Manufacturing 26
    3.3.3 Manufacturing 27
    3.3.4 Computing and Artificial Intelligence (AI) 28
    3.3.5 Communications and Sensing 30
    3.3.6 Energy 32
    3.3.7 Vehicles 33
    3.3.8 Space 36

4. DISCUSSIONS/CONCLUSION 38
  4.1 Results 38
  4.2 Limitations 39
  4.3 Further work 41

ACKNOWLEDGEMENTS 42

5. REFERENCES 43

APPENDIX A : PERSISTENCE SCORING METHODOLOGY 50

APPENDIX B : TECHNOLOGY CONCEPTS 53
- **B.1 Life Sciences 54**
  - B.1.1 Pharmacy/Medicine/Food 54
  - B.1.2 Analytics and Sensing 55
  - B.1.3 Biological augmentation and Human-machine interfaces 56
  - B.1.4 Biomimetics and synthetic biology 57
- **B.2 Materials and Manufacturing 58**
  - B.2.1 Materials 58
  - B.2.2 Manufacturing 60
- **B.3 Computing and Artificial Intelligence (AI) 61**
  - B.3.1 Information processing and computing architectures 61
  - B.3.2 AI 62
  - B.3.3 Simulation and training 63
- **B.4 Communications and Sensing 63**
  - B.4.1 Sensing and Navigation 63
  - B.4.2 Secure Communications 65
- **B.5 Energy 66**
  - B.5.1 Directed Energy 66
  - B.5.2 Energy Generation and Storage 66
- **B.6 Vehicles 68**
  - B.6.1 Propulsion 68
  - B.6.2 Configurations 68
  - B.6.3 Unmanned and Autonomous Systems 69
- **B.7 Space 70**
  - B.7.1 Guidance and Control 70
  - B.7.2 Configurations 70

List of Tables

Table 3-1 Summary of persistent future challenges to global security and defence 16
Table 3-2 Examples of the key terms used in this section 17
Table 3-3 Future technology application areas ranked according to their relative persistency 21
Table A-1 Range of scores for Reliability 51
Table A-2 Calculation of a Persistency score for a single future technology area, titled "Bio-mechanical robotic integration and biomimetic devices". 51

List of Figures

Figure 1. Flow-chart of the scoring process used to create an unbiased estimate of the independent prevalence of future technology concepts 9
Figure 2. A chart of technology themes indicating their proportion of aggregate persistency across the future technology literature considered within this study 19
Figure 3. Coding scheme for the literature weighting process (repeated from Figure 1) 52

List of Acronyms

ABCA	(Nations) America, Britain, Canada, Australia
AI	Artificial Intelligence
AIDS	Acquired immunodeficiency syndrome
approx.	Approximately
ASAT	Anti-Satellite
AU	Air University (US)
BMI	Brain-Machine Interface
BRIC	(Nations) Brazil, Russia, India, China
btw.	Between
BWA	Biological Warfare Agent
CB	Chemical, Biological
CBRN	Chemical, Biological, Radiological, Nuclear
CNRP	Carbon Nanotube Reinforced polymer
CNT	Carbon Nanotube
CO2	Carbon Dioxide
DE	Directed Energy
DEW	Directed Energy Weapon
DNA	Deoxyribonucleic Acid
DSTO	Defence Science and Technology Organisation (Australia)
EA	Electronic Attack
EMP	Electromagnetic Pulse
EO	Electro-optic
ETA	Estimated Time of Arrival
EU	Europe or European Union
EW	Electronic Warfare
F2T2EA	Find-Fix-Track-Target-Engage-Assess
GEO	Geosynchronous Orbit
GPS	Global Positioning Satellite
HAA	High Altitude Airship
HALE	High Altitude, Long Endurance
HIV	Human Immunodeficiency Virus
IADS	Integrated Air Defence System
ICT	Information and Communications Technology
ID	Identification
IEA	International Energy Agency
IMF	International Monetary Fund
IR	Infrared
ISR	Intelligence, Surveillance and Reconnaissance
IT	Information Technology
LEO	Low-Earth Orbit
MAV	Micro Aerial Vehicle
MEMS	Micro Electro-Mechanical Systems
MMOG	Massively Multiplayer Online Game
MoD	Ministry of defence
MRAM	Magneto-resistive Random Access Memory

MW	Megawatt
NA	Not Available
NASA	National Aeronautics & Space Administration (USA)
NATO	North Atlantic Treaty Organisation
NEMS	Nano Electro-Mechanical Systems
NIC	National Intelligence Council (US)
NISTEP	National Institute of Science and Technology Policy (Japan)
NRL	Naval Research Laboratory (USA)
OECD	Organization for Economic Cooperation and Development
OODA	Observe, Orient, Decide, Act
PNT	Positioning, Navigation and Timing
RAND	Research and Development Corporation (US)
RAM	Rockets, Artillery, Mortar/Random Access Memory
RBCC	Rocket-Based Combined Cycle
RF	Radio Frequency
RNA	Ribonucleic Acid
SA	Situational Awareness
SEAD	Suppression of Enemy Air Defences
SME	Subject Matter Expert
SSA	Space Situational Awareness
SSTO	Single Stage to Orbit
TA	Technology Assessment(s)
TBCC	Turbine-based Combined Cycle
TRL	Technology readiness Level
TST	Time Sensitive Target
UAS	Unmanned Aerial System
UAV	Uninhabited Aerial Vehicle
UCAV	Uninhabited Combat Aerial Vehicle
UK	(Nation) United Kingdom
UN	United Nations
US	(Nation) United States
USAF	United States Air Force

1. Introduction

Technological innovation has had a great influence on military air operations. The Royal Australian Air Force (RAAF) recognises the importance that technology developments have played in both war and peace-time operations [1] while the USAF talk about using science and technology (S&T) to "create the future" [2]. To gain a better understanding of the path of technology development, Air Force Headquarters (AFHQ) asked the Defence Science and Technology Organisation[1] (DSTO) to examine the following question:

"What new areas of technology might be available in the 20-50 year timeframe that should influence how Air Force develops current and future forces?"

The work presented here is a review of the literature describing anticipated future developments in a wide range of technologies. The aim is to present a list of technology developments that may arise within the 2030 and 2060 timeframes. This will inform subsequent studies that will consider the potential implications of such technologies on Australian air power.

1.1 Approach

The literature covering anticipated developments in technology is large and of varying authority. To facilitate the task of reviewing this literature, a scoring scheme has been developed in an attempt to give an unbiased ranking of the significance of different technologies. Key features of the approach used here are that it weighs the apparent authority of the source as well as applying weightings based on the independence of the source. The aim of the second factor is to prevent over representation of multiple sources from similar organisations and cultures. Chapter 2 and Appendix A give the rationale and details of the method.

The primary aim is to present information on specific technologies and their application areas. For context, however, it can be helpful to consider environmental trends and drivers. Such considerations can then be used to identify anticipated needs or societal pressures that may influence the emergence and development of specific technologies. A summary of the dominant views on environmental trends and drivers is included in Chapter 3.1.

Chapter 3.2 presents the results of the literature scoring scheme with the 100 highest scoring technological developments identified. Chapter 3.3 follows with a narrative proposing possible developmental paths for different areas of technology within the context of plausible developments in the external environment.

---

[1] This has been formalised through DSTO task AIR 07/036 - Support for the Future Air and Space Capabilities.

Discussions of the results and limitations of the approach used here are presented in Chapter 4. Also given here are recommendations for future work that would test and further improve the method developed here for carrying out a literature review across such a broad range of topics.

2. Method

2.1 Study Assumptions

The main assumption of the work presented here is that an accurate forecast of technological developments out to 20+ years is not possible. Instead, the intended outcome of this study is a plausible narrative about a range of directions technologies may take in the future. This will provide a background for the overall activity aimed at assisting the Royal Australian Air Force with exploiting emerging opportunities and planning for the future, including decisions on acquisition, research and development and workforce planning.

2.1.1 Accuracy of forecasts

Some authors claim that it is possible to predict short term trends (up to 10 years) by extrapolation of current trends, prediction markets [3] (months) or other methods [4]. However, these methods do not work consistently and there are numerous examples where future technology predictions have been wrong. Worlton [5], gives examples of expert predictions from 1937 that failed to predict significant technologies that appeared less than ten years after these predictions were made. These included jet aircraft, radar, nuclear energy, antibiotics and computers. Worlton also quotes results from another study that shows forecasting accuracy declining exponentially with time for controlled, expert-made predictions[2]. Suggestions for key factors as to why long-term predictions are wrong include:

- Cyclic technological change with unpredictable technology disruptions occurring at either end of the cycle [6, 7]. These sources suggest that technology improvement follows the shape of an S-curve cycle that can last from one to several decades. For example, Chang [6] shows how for energy, vehicle and computing technologies, the operational performance of new technologies, once unexpectedly introduced is more than 50 times better than the technology that has been replaced.
- Modern technology assessments (TAs) of concepts with the greatest potential for disruption (such as nanotechnology) are changing at rates that cause significant uncertainties at even short-term timescales [8].

Despite the long-term unpredictability of future events and technologies, estimates of plausible time horizons of future technologies can guide, rather than dominate, the development of strategy and plans.

---

[2] In fact, Worlton [5] suggests that any prediction beyond a three (3) year horizon “should be considered dubious”.

2.2 Requirements Pull and Technology Push

This study considered the following two broad domains:

- **environmental trends and drivers:** also known as requirements pull
- **emerging and future technologies:** also known as technology push.

This study is primarily focussed on collecting data for Emerging and future technologies, but it was decided that an understanding of the environments in which these technologies may arise is important for context.

2.2.1 The literature on environmental trends and drivers

It is widely accepted that environmental drivers such as social, economic or geopolitical pressures affect technology development [8-11]. For example, the requirement for astronauts to have access to fresh water, led NASA engineers to develop technologies in 1995 and 2006 that produce drinkable water from wastewater. The technology was adopted by the commercial sector to benefit communities across the globe where access to fresh water is limited [12]. Experts estimate that the development of advanced water purification technologies may be driven by dense population centres in developing countries having limited access to clean water [10, 13].

It is surmised that if the requirements pull is sufficient, advanced water purification technologies may have an increased likelihood of being developed sooner. This is also analogous to the large technological leaps achieved during the Apollo space program when the funding of the space program was, on average, 4% of the total federal budget between 1964 and 1966 [14]. High levels of technology investment can be seen in parallels of ICT in the late 20th and early 21st centuries; or development of weapons technologies during the Second World War. Similar major requirements pull trends were identified and are reported on in Chapter 3.1.

A number of reputable reports on expectations for the future global environment are publicly available. These are in the form of official reports commissioned for national governments including Australia, Canada, UK, US and China; and international organisations such as the UN, the Organization for Economic Cooperation and Development (OECD) and the International Energy Agency (IEA). The environmental trends serve to illustrate the societal pressures that may influence the emergence and development of specific technologies between 2030 and 2060. Chapter 3.1 of this report presents the results of the analysis of the environmental trends and drivers.

2.2.2 The literature on emerging and future technologies

The literature on the future of technology is vast and, therefore, far more challenging to analyse. Mays and Pope [15] recognise the benefit of increasing sampling and qualitative data volumes as a way of improving the reliability of qualitative research. They suggest the use of quantitative tools to supplement the workload-heavy tasks of summarising raw data. Janasik et al. [16] have demonstrated that certain text mining approaches can result in improving inference quality in qualitative research of large data sets. Further, they have shown that the use of automated textual analysis is less vulnerable to researcher bias. Therefore, an improvement to human-only analyses of large textual data sets for futures research under this task would be to use a software tool for automated text analysis. The time and effort involved in implementing the processes recommended above was beyond the resources available for the study presented here. Nevertheless, the implementation of a consistent approach to analysing the literature relatively quickly and easily was required. Described in the following section is a novel method for analysing these data that has been developed and implemented here.

2.3 Method for filtering the technology forecast literature

The following outlines the process used to filter out the useful information amongst the broad range of literature on technology forecasts. The process described here is designed to quickly and easily address the following:

1. the volume and diversity of presentation of information is large
2. there are many viewpoints
3. the quality of information is variable.

These issues are described in greater detail below.

Issue 1: Volume and diversity
The amount of open-source material related to future technology and technology forecasting is huge[3] and the information is presented in a myriad of ways:

- there are those who detail a few technologies and their ramifications on society, while others discuss many superficially
- some weave their story into ideas about the future state of the world, in terms of the attitudes of the superpowers or the individual
- there are attempts to address forecasting methods and the challenges of making forecasts
- those who document the results with facts and scientific evidence while others write narratives similar to science fiction authors.

Issue 2: Viewpoint
Mainstream ideas are easily identified; they are discussed widely in the literature and by many authors. These ideas have often been peer reviewed. Evidence is often presented in the form of trends giving apparent authority to the forecast. There is also value in seeking non-mainstream ideas that show independent thinking or have come from a unique viewpoint; these ideas will help with avoiding the trap of group-think. The drawback,

---

[3] After filtering, the final number of useful information sources was 105. This is approximately 20% of the initial total number of sources.

however, is that by including more unconventional ideas, the literature and the workload grow.

Issue 3: Reliability
There needs to be some assurance that the collected data meet a minimum standard of quality. Included in this analysis are data from reliable sources and care has been taken to separate informed opinion from imaginative speculation. Acceptable sources are those where the author is known and is:

- an experienced futurist, or
- a technical expert, or
- a body/panel commissioned to conduct an extensive study using recognised futures methods such as Delphi, interviews or workshops to develop their ideas.

This approach allows a minimum quality standard to be set for all the source material.

2.4 Information Scoring

Having filtered the data as described above, the following summarises the process that assigned a score to the remaining information according to:

- methods - whether individual or group perspectives generated the information
- cultural independence
- frequency.

These criteria are embodied in a scoring process that is summarised in Figure 1 and detailed in Appendix A. This scoring process is the basis of the simple scheme designed to prioritise the collected information. The scheme assigns a numerical weighting for each criterion. A total score is awarded to each piece of new information by collecting all of the individual weightings that relate to the same future technology area.

Criterion 1: Methods
The collected data considered perspectives gleaned from sources that included multi-expert (consensus[4]) surveys and panels as well as individual SME perspectives.

Large-scale studies, using multi-expert surveys, representing the contributions of numerous experts shared the following characteristics:

- They spanned a broad range of technology areas.
- They captured a wide range of opinion.
- They were more likely to employ SMEs.

---

[4] Consensus, in this context, is about the agreement of SMEs within a foresight or forecasting activity that results in a specific set of projections about the plausible state of the future. A lack of consensus is representative of individual SME opinion instead of collective judgement.

- They used consistent methods to elicit expert opinion.

On the other hand, SME opinion sourced from individuals exhibited the following characteristics:

- They spanned a very limited set of technology areas.
- They were often ambiguous in their findings.
- Their methods were more often unknown than those of multi-expert studies.

Therefore, information was treated more favourably from sources employing multi-expert consultations as part of a larger futures activity than information from sources that did not. A maximum number of points (2) were awarded to multi-expert views for Criterion 1 and a lower score (1), was awarded to individual expert views.

For example, multi-expert studies commissioned by the UK MOD [17], the USAF [18] and the Japanese government [19], were ranked more favourably to individual perspectives from futurists or other experts involved in the art of technology forecasts.

Although ranked differently, the inclusion of both multi-expert and individual expert perspectives is important to help reduce the effect of group-think.

Criterion 2: Cultural Independence

Similar estimates of future developments arose from sources with:

- similar socio-cultural backgrounds (same country of origin); or,
- strong research links and collaborations (across separate countries); or,
- shared perspectives of what the future trends are (explicit mention of shared scenarios).

Use of source material from the same country, institutions that worked closely together; or where the assumptions of future trends were shared (for example, use of shared scenarios in planning), increased the risk of not generating a sufficiently diverse analysis. The view taken here is that opinions on future technologies shared among culturally disconnected studies add weight to these data. If sources A and B are considered culturally independent, but hypothesise about the same technology X; then X's plausibility is reinforced. The assessment for whether sources are culturally similar or independent is based on whether there exists another reference amongst the reviewed literature that shares both the same country of origin and was published within two years[5] of the original reference. Information from culturally independent sources was awarded a maximum of one (1) weighting points. If an idea has only one supporting source, it is considered

---

[5] The underlying rationale builds on an assumption, supported by at least one other author [20]. Namely, that the effect of recency bias is significant when human judgements are made during forecasting. A period of two years was chosen here as being a suitable length of time in which a previous study is less likely to influence current thoughts on future trends; the appropriateness of the length of time chosen here could be the subject of further study.

culturally independent within this body of sources. Culturally similar ideas were awarded a score of zero.

Criterion 3: Frequency
Mainstream expert views dominate the source material. This criterion ensures that the analysis has the means to include both mainstream and more unconventional ideas.

This criterion tracks new ideas about future technologies by counting each occurrence. This creates a measure of frequency of occurrence of individual technologies across multiple sources. For each repeated occurrence, the count is incremented by one (1). A total frequency score is then assigned to each technology area or concept that was identified amongst the future technology data.

The scheme calculates the total *persistency* score (*P*) for each identified future technology area or concept as shown in Figure 1. More detail on the development and application of this scoring scheme is included in Appendix A. The aggregated catalogue of future technologies that appears in Appendix B is ranked according to each entry's persistency score.

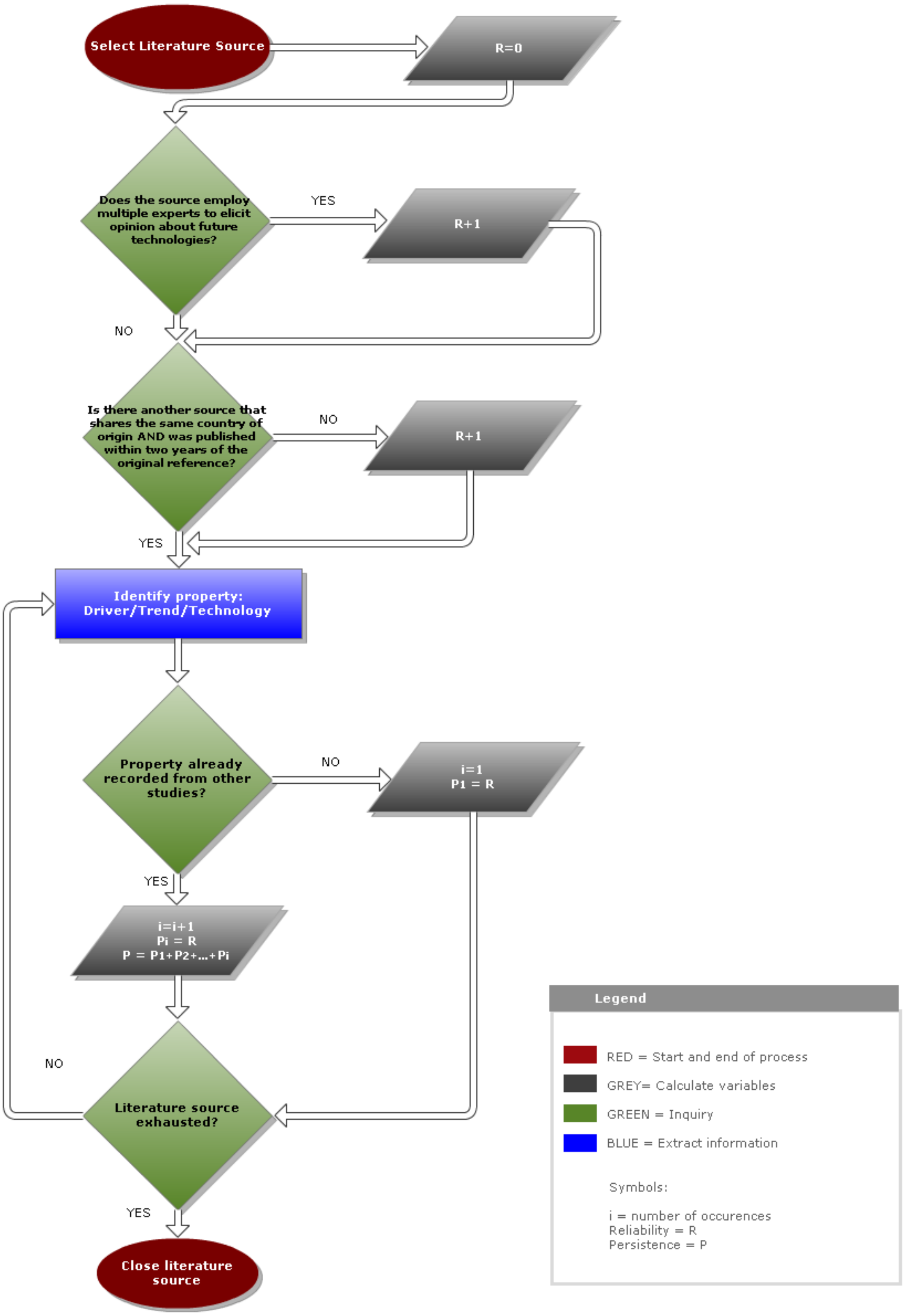

Figure 1. Flow-chart of the scoring process used to create an unbiased estimate of the independent prevalence of future technology concepts

The ranked data on future technology concepts is summarised in Chapter 3.2. That summary includes information addressing the above data capture requirements and includes the following:

- technology: the name of a technology area or concept being described
- cross-disciplinary effects: other plausible technology application areas that the described technology may be used in
- application examples: literature-sourced examples of plausible ways of applying this technology
- horizon: information about technology maturation timeframes – plausible within the context of the study assumptions.

3. Results

The following chapter contains the outcomes of the analyses of the literature on future environments and technologies. Chapter 3.1 describes the environmental trends and drivers and Chapter 3.2 outlines the prioritised list of plausible future technologies. The reader should refer to Appendix B for a detailed list of individual technologies and references to original sources used in support of this analysis.

Combined, the results from both analyses are woven together into a narrative about future technological change within the background of a plausible future world in Chapter 3.3. This narrative creates an accessible medium that will inform the reader about a diverse range of plausible future technologies identified in this scoping study.

3.1 Environmental Trends and Drivers

Information about the environmental trends and drivers affecting the human environment provides the context for how humans interact with their environment. The interaction of humans with their physical, social and geopolitical environments was most recently identified as the most important driver of change in a large-scale government foresight activity [17], which drew on UN, OECD and a comprehensive range of expert opinion collected between 2004 and 2010.

The sources on environmental trends and drivers used here were reports from the governments of the US, UK, Canada, China and organisations such as the UN, OECD and IEA. The following sections illustrate future societal needs or other external environmental pressures. Examples of how technologies could develop in response to such issues are provided where identified. Because the majority of the literature review was focused on technological rather than environmental developments, the data on environmental trends and drivers offers a more limited perspective. The remainder of this chapter provides brief summaries of the dominant environmental trends and drivers presented in these sources.

3.1.1 Physical Environment

The physical environment includes issues related to climate change, availability of natural resources and energy and the impacts of natural disasters.

Possible changes in the physical environment include:

- Atmospheric warming affecting the production of energy, supplies of food and freshwater [17].
- Food and water shortages due to increasing desertification and/or changing rainfall patterns [21].
- Increased intensity of weather-borne natural disasters [22].

- Increasing attempts to reduce environmental impacts of technologies and operations [22].
- Growing industrialization and development leading to increasing pollution of freshwater supplies [23].
- Accessible oil and gas not matching demand[6] [24] by 2020 and markets becoming increasingly volatile with fuel price fluctuations.
- Exploitation of unconventional oil sources such as Canadian oil sands and Venezuelan extra-heavy crude oil exploitation [24].
- Nuclear power may become increasingly proliferated as fossil fuels are phased out. Increased and sustained investments in nuclear energy such as 3rd generation fission reactors [25] and in modern renewable technologies may occur by 2040 [17].
- Exploitation of extreme environments is likely to occur if easily accessible supplies of energy, food, water and minerals continue to dwindle. Deep ocean, polar and deep underground regions are likely to be explored [17, 26].

Possible key technology trends developing in direct response to changes in the physical environment may include:

- Genetic and scientific modification of crops may be used to improve yields of crop and livestock in a range of challenging environmental conditions [17].
- Switching away from fossil fuels to other forms of energy, such as low carbon energy, especially in developed countries that can afford the development and implementation of new energy technologies [10, 25].
- New and sustainable agroeconomic methods have been identified by the UN [27] as potentially offering a solution to expected acute food shortages.
- Development of more sophisticated prediction tools and sensory networks [28].
- New refining technologies [24] for fossil fuels.
- New generations of biomass could emerge to provide viable alternatives to fossil fuels [29].
- Finite uranium reserves will require developments in new types of reactors and associated facilities in order to make nuclear power more attractive. Technological breakthroughs in nuclear fusion could occur but a viable fusion reactor is unlikely before 2040 [17].
- Exploitation of extreme environments has significant engineering challenges which will stimulate technological innovation across many areas [17, 26].

---

[6] While these estimates fluctuate consistently, the latest International Energy Agency report on energy futures out to 2035 [24] placed the peak oil event between 2020 and 2035. 2020, being the most conservative (earliest) estimate.

3.1.2 Social Environment

The social environment, traditionally characterised by mass human interactions could, according to UK [17] studies, be dominated by demographic change such as population increases, ageing, youth bulges and the impacts of cultural globalisation. Other social factors may also play a part in how new technologies may develop or diffuse within societies.

Possible changes in the social environment include:

- Contingent on continuing improvements in HIV/AIDS prevention and treatment (even assuming reductions in overall birth rates), the world's population is likely to increase, especially in developing countries [30].
- The UN expects that by 2050, populations on the Arabian Peninsula could more than double in size [31] – with disproportionate increases in youthful populations. Several studies [10, 17, 26] recognise that demographic change will include after-effects of increasingly ageing populations in developed countries and youth bulges (ages 12-24) in developing countries.
- Future youth-driven crises may be driven by regimes failing to find solutions to socio-economic problems. As youthful populations increase, the pressure on education, housing and employment opportunities are expected to increase. Significant security challenges may arise when social expectations are not met as a result of population and demographic pressures [32].
- Increasingly limited access to fresh water, food and sanitation because infrastructure developments are likely to continue to lag behind population increases [23].
- Ageing populations may result in societies whose health and employment prospects may be worse off than at present [33].
- The UN suggests that by 2050, 70% of the world's population could live in urban areas [34], resulting in high population densities.
- Numbers of mega-cities[7] are likely to increase and are projected to account for 10% of the world population by 2025 [34] placing further stresses on civic infrastructure.
- The Internet is expected to enable seamless and intuitive facilitation of social connections and information sharing beyond local communities, languages and cultures [28].

Possible key technology trends developing in direct response to changes in the social environment may include:

- Technological innovation may be sought to aid congestion, reduce pollution and fight outbreaks of disease [28] in dense population centres.

---

[7] Cities with greater than 10 million inhabitants

- Technology advances might provide integrated cyberspace capabilities augmenting traditional sensory experiences [28].
- Large data quantities stemming from ubiquitous sensor networks could continue to stimulate developments in massive analytics and may help develop sophisticated computing architectures [28].
- Current advances in Information and Communications Technology (ICT) along with the pervasiveness of digital media and communications are expected to continue. Natural language translations and universal connectivity are likely to be developed [10].
- Possible inhibitors to technological progress exist in the form of ethical opposition to new technology implications in ethically conservative societies. This is particularly true of biomimetic technologies, synthetic organisms, DNA manipulations, human augmentations and developments of autonomous, AI-driven systems [28].
- Possible technology developments in life-sciences, manufacturing, materials and transport may be required to ameliorate infrastructure stresses [28].
- Innovation in techniques and technologies for modelling human behaviour could improve government-level decision making and ease urban planning [28].
- The demand for technological developments in medicine, bioengineering and pharmaceuticals could continue to grow in response to ageing populations' needs [10, 17].
- Advances in medical technologies, extending lifespans [10].

3.1.3 Economic Environment

If it is assumed that strong economies will have the capacity to develop and acquire a wider range of technologies, a significant amount of research and development (R&D) expenditure is expected to remain westernised (US, Germany, France, the UK, Canada, Italy) and shared with close East Asian allies (Japan, South Korea), despite the economic rise of nations such as China and India. This is reflected by a comprehensive US report on Science and Engineering Indicators [35] which shows that the US, Japan, China, Germany and France account for 66% of the global R&D expenditure. With the addition of South Korea, the UK, Russian Federation, Canada and Italy, 80% of the world's R&D expenditure becomes represented. These research priorities are expected to shift along the same lines as economies. Expected changes in the economies of several countries were used to illustrate potential changes to corresponding investments into S&T. Care should be taken to include expert perspectives that could close the gap in western understandings of emerging technologies from countries such as China, which are expected to reach and surpass R&D and economic parity with its western counterparts [17]. Studies undertaken by the International Monetary Fund (IMF), World Bank and PricewaterhouseCoopers [36] were consulted in obtaining some general information regarding the patterns of global economic change over the next 20-50 years:

- Greater economic globalisation, is seen as likely to increase global knowledge circulation and the proliferation of technology across different markets [10, 28].
- Changes in global economic leadership were seen as a second major trend which could potentially shift the loci of innovation to new markets with radically different research priorities [10, 28].
- Disparate markets will have increasing exposure to subject matter experts due to increased global interactions and interconnectivity of research hubs [28]. Globalisation and the associated "brain circulation" of SME is likely to generate diverse technological interconnections and cross-disciplinary S&T applications [10, 17, 28].
- Economic globalisation and the shifting of regional economic influences is expected to continue to aid S&T proliferation and development [28].
- There may be attempts to de-globalise local markets and reduce exposure to externally-derived risk by modelling the entire global economic system with sophisticated simulations and AI agents [10, 28].
- IMF and World Bank projections (as cited in [17]) show that EU and US shares of the world economy may shrink and become equal to China sometime after 2020.
- India is expected to rise accordingly, to reach near-parity with the declining EU and US shares by 2050 [36]. The economies of Brazil and Russia are expected to grow substantially during the same period and overtake those of France, UK, and Germany [36].

3.1.4 Security and Defence

Changing security and defence needs of countries could have the greatest direct technological impact on those states that have the largest defence R&D budgets. Countries with the largest R&D budgets, in general will also continue to be affected by such developments even if their S&T programs do not have direct military applications in mind. While reliable data on R&D military expenditures remains difficult to obtain for most countries, total military spending per country is tracked by several organisations[8]. However, defence spending may be disproportionately used on the acquisition of technologically proven capability and through-life costs, rather than actual research. Instead, data on total R&D expenditures as a relative measure of defence R&D spending was used to approximate the relative military R&D spending. A US government report on global R&D spending [35] lists significant contributors to global R&D efforts such as the US (33% global R&D expenditure), EU (25%), Japan (13%) and China (9%). Because of such disproportionate spending in comparison with the rest of the world, and the fact that fieldable technology takes decades to develop, current indicators may be useful in estimating near to medium-term leaders in the development of new military technology. Therefore, it is these countries, that may have the greatest influence on the developments

---

[8] The Stockholm International Peace Research Institute combines data from sources such as national governments and United Nations, NATO, International Monetary Fund (IMF) and other reliable secondary sources [37].

of military technology based on indigenous civilian and military programs. Changes in perceptions of future security environments for these countries are likely to affect how the military applications of civilian technologies and outright developments of military technologies will occur.

Reports on future security and defence needs from countries such as the US, UK, Canada and China[9] were consulted to create a list of strategic trends expected to be influential from 2020 onwards. Information from these nations resulted in some key overarching trends, taken to be representative of the context in which future security and defence environments could develop. Table 3-1 summarises persistent trends in the future security and defence environments according to a number of separate sources and offers a hybrid picture of a wide range of security and defence themes brought up in literature. All explicitly stated trends for each of the referenced sources are included and the most prevalent ones ranked first. Military integration of future technologies is likely to address the issues shown in Table 3-1.

Table 3-1 Summary of persistent future challenges to global security and defence

Defence Needs/Challenges	US [40]	UK [17]	Canada [26]	China [13, 38, 39]
Extreme Environments	•	•	•	•
Remote Operations	•	•	•	•
Contested Environments	•	•	•	•
Survivable Platform	•	•	•	•
Large Lift	•	•		
Fast Lift	•	•	•	•
Cyber	•			•
Rapid Space Reconstitution	•	•	•	
(Counter) Stealth	•			•
Asymmetric	•			•
Precision	•			•
Orbital And Space	•		•	•
Advanced Sensors	•	•		
EMP Threat	•			
Counter Air	•			
Technology Proliferation	•			
Ranged/Rapid Strike	•	•		
Humanitarian Ops.	•			
CBRN Threats	•	•		
Adversarial Social Networks	•	•	•	
Congested Battlespace	•	•		
Information Ops.	•	•	•	
Expeditionary	•			•
Persistent SA	•		•	
Full Spectrum EW	•			

---

[9] An accessible, native Chinese perspective relevant to the study timeframes was not found in literature. Instead US analyses [38] of future Chinese defence needs were used to provide the relevant strategic information. A Chinese report on future technologies [13] contained vague references to military technologies that echoed perceptions of Chinese security needs reported on in US publications [39].

3.2 Emerging and Future Technologies

This literature analysis identified seven broad application areas of emerging and future technologies that could become operational in the near (<10 years), medium (10-20 years) and long-term (>20 years) future. This captured future technology applications whose conceptual prototypes were emerging now but that would not become feasible until the 2030 timeframes or beyond. By identifying these early technology enablers, more mature concepts developed from such emerging technologies are identified here.

Tabulated lists of future technology applications, estimated emergence timeframes and their cross-disciplinary applications were developed and are given in Appendix B. The entire inventory of technologies was themed and linked to the corresponding environmental trends and drivers presented in Chapter 3.1. These results are used to generate both a table (Chapter 3.2, Table 3-3) and a narrative (Chapter 3.3) aimed at informing studies about the broad range of future technology applications between 2030 and 2060.

3.2.1 Overview

The relationship between a technology theme (broad); a technology application area (specific); and a technology concept (detailed) is illustrated in the following table (Table 3-2). Each technology theme contains a subset of related future technology application areas. Each technology application area describes the conjectured use case of multiple technology concepts. The reader should refer to Appendix B for a complete list of technology application areas clustered around broad themes, including references to original sources where specific concepts are mentioned. The remaining sections (Chapters 3.3.1 to 3.3.8) present the main narrative of the outcome of this study that used the collected data to present an accessible account of future technological change.

Table 3-2 Examples of the key terms used in this section

TERM	EXAMPLE
Technology Theme	Life Sciences: Biomimetics and synthetic biology
Technology Application Area	Bio-mechanical robotic integration and biomimetic devices
Technology Concepts	Introduction of biomimetic implants [7] and biologically inspired mechanical concepts [54]. Remote control of insects in flight [55]. Development of bioelectronic devices [16]. Application of biomimetic robotics [6]. Autonomous decision making on robotic platforms [30]. Intelligence [sic] service robots [9].

3.2.2 Persistent technologies

The data supporting technologies were themed within broad taxonomic descriptions. These technology themes best encapsulate the broad qualitative patterns of technological change in the collected data. The themes also reflect the technology research areas that DSTO has broadly dealt with throughout its support of ADF's S&T interests. Seven broad technology themes were thus identified:

- Life sciences
- Materials and Manufacturing
- Computing and Artificial Intelligence
- Communications and Sensing
- Energy
- Vehicles
- Space.

The results presented here used the persistency scoring approach described in Chapter 2 and Appendix A. A persistency score is a surrogate measure of the popularity, or the prevalence of a particular technology within the analysed literature. Technology application areas with high persistency; such as "Life Sciences" and "Materials and Manufacturing" (Figure 2), form a significant part of the current mainstream focus on future technologies. Conversely, "Space" - a technology theme with the lowest aggregate persistency score – does not appear to be a common topic within this body of literature. Figure 2 shows how prevalent the technology themes have been in the consulted literature. Figure 2 can thus help determine which broad technology areas may require additional analyses, given a predisposition towards capturing information that was more persistent.

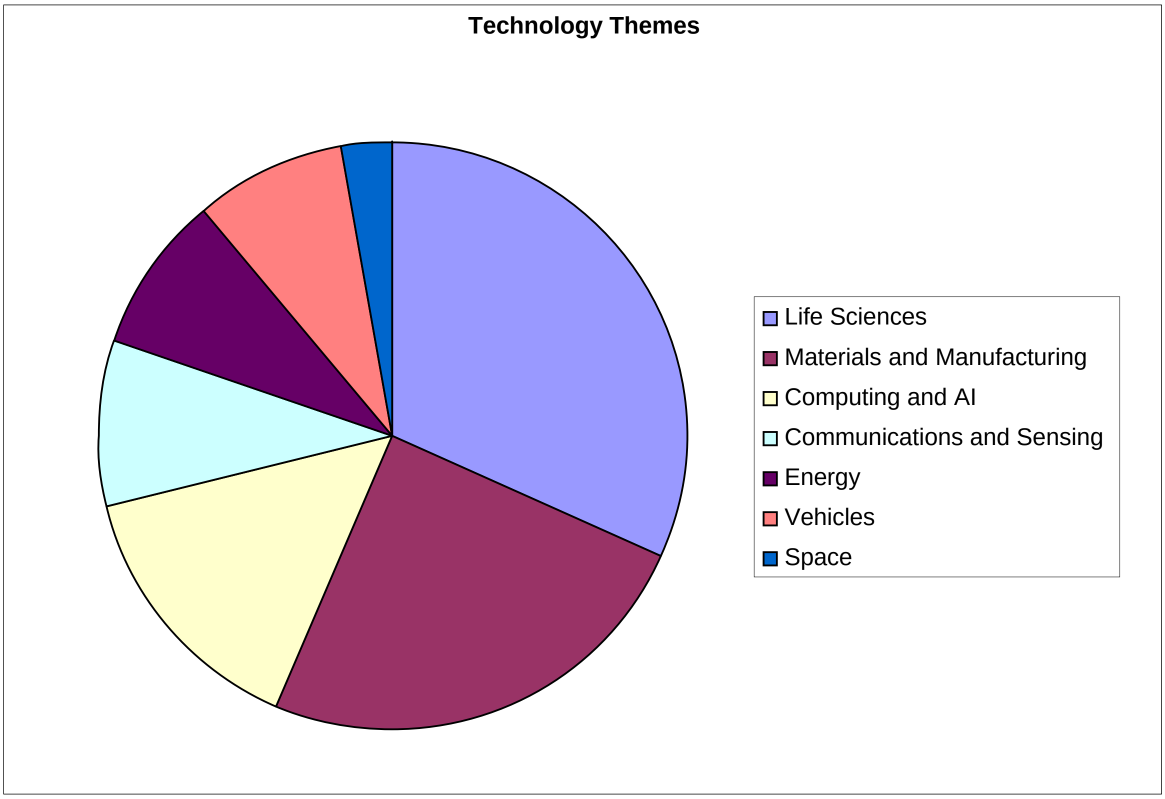

Figure 2. A chart of technology themes indicating their proportion of aggregate persistency across the future technology literature considered within this study

The reader can refer to Appendix B for an overview of technology areas and associated technology concepts; along with detailed descriptions, literature references, maturation timeframes and quantitative measures of persistency. Table 3-3 is a list of all technology application areas sorted according to relative persistency. Each persistency score is an indication of how mainstream the perspective on that future technology was, at the time these data were captured. These results present the reader with an overview of whether the application of future technologies, in the ways described, can be considered mainstream or esoteric in nature.

The entire data set in Appendix B also suggests other application areas relevant to the underlying technology concepts. These *cross-disciplinary effects* outline the specific technology themes that could hold important, but alternate application areas for the identified technology concepts. These could be used to identify concepts that share seemingly disparate technologies. An example is NASA's proposed use of biomimetic principles, carbon nanotubes, and embedded-health monitoring to developed a new shape-adaptive aerospace platform [42]. In this real-world example, the reader could have used the table given in Appendix B to see that *"Bio-mechanical robotic integration and biomimetic devices"* has a cross-disciplinary effect on *"Aerodynamic Configurations"*. Likewise, *"Carbon nanotubes"* have an identified cross disciplinary effect on *"Vehicles"*. The reader could have drawn the parallel, without knowing about NASA's future concept, that some form of a carbon-nanotube aerospace vehicle using biomimetic principles was possible.

Table 3-3 lists 100 technology applications ranked according to their persistency that may become operationally or commercially viable within the timeframe of interest (2030-2060). It provides the reader with a prioritised list of future technology application areas; ranging from the most mainstream to the most esoteric perceptions of future change identified within the analysed body of literature. This table does not contain any of the underlying technology concepts or cross-disciplinary effects. For that level of detail, the reader should refer to Appendix B.

Table 3-3 Future technology application areas ranked according to their relative persistency

Technology application area	Maturation timeframes	Relative persistency	Tech. Area[a]
1. Nanomaterials and structures	btw. 2018 & 2030	100	Life Sci.
2. Bio-mechanical robotic intergration and biomimetic devices	btw. 2020 & 2035	100	Mats. & Manf.
3. Computational drug design and testing	btw. 2020 & 2060	83	Life Sci.
4. Bio-factories and biological substrates	btw. 2020 & 2030	75	Life Sci.
5. Artificial implants for improvements or recovery of biological functions including brain-machine interfaces	btw. 2020 & 2030	67	Comp. & AI
6. Accurate prediction and modification of human behaviour and intent	btw. 2020 & 2030	67	Life Sci.
7. Drug delivery and targeting including personalised treatments using molecular recognition	btw. 2015 & 2020	67	Life Sci.
8. Advanced biometrics	btw. 2020 & 2030	67	Life Sci.
9. Bioinformatics	btw. 2020 & 2060	67	Life Sci.
10. Electronic materials	approx. 2020	58	Comp. & AI
11. Pharmaceutical or biological human performance modification	btw. 2020 & 2060	58	Comp. & AI
12. Room temperature ferromagnets and superconductors	approx. 2030	58	Comp. & AI
13. Next generation low observable materials	btw. 2020 & 2030	58	Life Sci.
14. Massive analytics	btw. 2020 & 2030	58	Mats. & Manf.
15. Carbon nanotube	approx. 2020	58	Mats. & Manf.
16. Quantum computing	btw. 2020 & 2060	58	Mats. & Manf.
17. Miniaturised high-density data storage	btw. 2020 & 2040	58	Mats. & Manf.
18. Virtual synthetic environments and adaptive training	btw. 2015 & 2030	50	Comms
19. Smart fabrics	btw. 2020 & 2030	50	Comp. & AI
20. Restoration/regeneration of human body parts	approx. 2020	50	Energy
21. Secure wireless links	approx. 2020	50	Energy
22. High-density/high-efficiency energy storage technology	approx. 2020	50	Life Sci.
23. Genetic modification of biological organisms	approx. 2020	50	Life Sci.
24. DNA microarrays, rapid bioassays and nanowire sensors	btw. 2020 & 2030	50	Life Sci.
25. Medical nanostructures for drug delivery	btw. 2011 & 2020	50	Life Sci.
26. Integrated machine control	btw. 2020 & 2030	50	Life Sci.
27. DNA fabrication techniques and nanomolecular manufacturing	btw. 2020 & 2030	50	Mats. & Manf.
28. Programmable manufacturing	btw. 2020 & 2030	50	Mats. & Manf.
29. Green chemistry and manufacturing	btw. 2020 & 2030	50	Mats. & Manf.
30. Biofuels and synfuels	approx. 2025	50	Mats. & Manf.
31. On-demand manufacturing	approx. 2020	50	Mats. & Manf.
32. Artificial Intelligence and autonomous, intelligent processing	btw. 2030 & 2040	42	Comms
33. Computational sociology and prediction of mass behaviour	btw. 2012 & 2030	42	Comp. & AI
34. Pervasive, undetectable sensor networks	btw. 2020 & 2040	42	Comp. & AI
35. Hypersonic air-breathing engines	approx. 2030	42	Vehicles
36. Reactive materials and structures	btw. 2012 & 2030	33	Comms
37. Software agents	btw. 2020 & 2030	33	Comms
38. Controlled fusion power	btw. 2030 & 2060	33	Comms
39. Autonomous swarming vehicles	btw. 2030 & 2040	33	Comp. & AI
40. Embedded health monitoring sensors	btw. 2020 & 2030	33	Comp. & AI

Technology application area	Maturation timeframes	Relative persistency	Tech. Area[a]
41. Widespread sensor networks	approx. 2020	33	Comp. & AI
42. Autonomous and self organising sensor networks	btw. 2030 & 2035	33	Comp. & AI
43. Highly portable or wearable inertial and position, motion and acceleration devices	approx. 2030	33	Energy
44. Nanobiology	approx. 2020	33	Energy
45. Water purification using nanotechnologies	btw. 2015 & 2030	33	Energy
46. Biological process identification and modelling	btw. 2020 & 2050	33	Life Sci.
47. Environmental models and complex simulations	btw. 2020 & 2030	33	Life Sci.
48. Neurochemical behavioural markers and mapping of high-order brain functions	approx. 2020	33	Life Sci.
49. Biomedical materials	btw. 2030 & 2060	33	Life Sci.
50. Quantum materials	btw. 2030 & 2060	33	Life Sci.
51. Semantic web	btw. 2020 & 2040	33	Life Sci.
52. Accurate wather forecasting	btw. 2020 & 2030	33	Life Sci.
53. Ad-hoc networks	btw. 2020 & 2030	33	Mats. & Manf.
54. Short-range laser defence	btw. 2015 & 2030	33	Mats. & Manf.
55. Microreactors	approx. 2020	33	Mats. & Manf.
56. Next generation high-efficiency turbine engines	approx. 2030	33	Mats. & Manf.
57. Metal-organic compounds	btw. 2012 & 2020	33	Mats. & Manf.
58. Silicon photonics	approx. 2017	33	Mats. & Manf.
59. Extreme manufacturing	approx. 2020	33	Vehicles
60. Laser communications	approx. 2030	33	Vehicles
61. Self-healing materials	approx. 2030	25	Comms
62. Supersonic/hypersonic bomber	approx. 2037	25	Mats. & Manf.
63. Hyperspectral and terahertz sensors	btw. 2020 & 2030	25	Vehicles
64. Hypersonic (attack) aircraft	btw. 2025 & 2032	17	Comms
65. Miniaturised radar for UAV and personal applications	btw. 2020 & 2030	17	Comms
66. Immersive optical interfaces	btw. 2015 & 2030	17	Comms
67. Specialised, high-performance coatings	approx. 2020	17	Comms
68. Tactical airborne laser	approx. 2030	17	Comms
69. MEMS flow control	NA	17	Comms
70. Wingman UAS	btw. 2020 & 2025	17	Comms
71. Synthetic biological engineering	approx. 2020	17	Comp. & AI
72. De-icing composites	approx. 2030	17	Comp. & AI
73. Nanowires	approx. 2020	17	Energy
74. Quantum chemistry	btw. 2030 & 2060	17	Energy
75. DNA computing	btw. 2030 & 2060	17	Energy
76. Immersive collaboration tools	approx. 2020	17	Energy
77. On-chip BWA identification	btw. 2020 & 2030	17	Energy
78. Stand-off laser detection of explosives	btw. 2015 & 2020	17	Energy
79. Hyperprecision munitions	approx. 2030	17	Life Sci.
80. 3D maritime environmental monitoring	approx. 2020	17	Life Sci.
81. Deep sea sensing	approx. 2020	17	Mats. & Manf.
82. Persistent near-space communication relays	approx. 2030	17	Mats. & Manf.
83. Femtolaser	approx. 2025	17	Mats. & Manf.
84. Microwave and RF DEW	approx. 2040	17	Mats. & Manf.

Technology application area	Maturation timeframes	Relative persistency	Tech. Area[a]
85. Next-generation nuclear reactors	approx. 2020	17	Space
86. Dual mode propulsion (supersonic/hypersonic)	approx. 2030	17	Space
87. HALE airships	approx. 2030	17	Space
88. Hybrid wing-body aircraft	approx. 2030	17	Space
89. Cyberspace UAV	approx. 2025	17	Space
90. Fractionated, survivable, remotley piloted system	approx. 2030	17	Space
91. Automated highways and vehicles for increased capacity and safety	btw. 2015 & 2020	17	Space
92. Unmanned space exploration	ongoing	17	Vehicles
93. Persistent SSA	approx. 2030	17	Vehicles
94. Orbital Conjuction Prediction	approx. 2030	17	Vehicles
95. Hypervelocity rod bundles for kinetic bombardment	approx. 2015	17	Vehicles
96. Reusable Airbreathing Access-to-Space Launch	approx. 2030	17	Vehicles
97. Rapidly Composable Small Satellites	approx. 2030	17	Vehicles
98. Fractionated/Distributed Space Systems	approx. 2030	17	Vehicles
99. Space-based lasers	approx. 2030	17	Vehicles
100. Future airborne laser	approx. 2030	17	Vehicles

[a] *Comp. & AI = Computing and Artificial Intelligence; Life Sci. = Life Sciences; Mats. And Manf. = Materials and Manufacturing; Comms. = Communications*

3.3 Future Technologies Narrative

The following narrative illustrates how future environmental changes may shape the use of a diverse range of identified future technologies. The narrative is not prescriptive. It does not serve to forecast future changes but merely suggests a plausible and wide ranging set of future technologies that may be of interest to stakeholders with an interest in long-term planning. Ideally, the reader will take into account the detailed findings about each technology area using the supporting information included in Appendix B. However, the following information should still present the reader with sufficient information to make informed judgements about future technologies with the confidence that all of the main takeaways are included in the remainder of this chapter.

3.3.1 Life Sciences

Life sciences and enabling technologies (such as ICT) are expected to primarily be driven by the changes in the social domain. Societal pressures of ageing, access to food, freshwater or energy, increasing global interconnectivity and commercial imperatives are expected to result in the swiftest advances to these technologies.

3.3.1.1 Pharmacy/Medicine/Food

Better drug delivery, vaccine development, water purification and biofilters could be developed to address future needs of societies. Advances in genetic engineering, in particular, would provide an enabling scientific basis for much of the improvements in personalised medicine and drug therapies. Techniques in modelling and simulation of biological systems (biosimulation) may enhance many of the underlying concepts enabling future research applications such as computational drug testing and predictive medicine. Combined with nanotechnology, the rapidly developing fields of computational biology could create a disruptive field of “nanobiology”. Cross-disciplinary developments could result in miniaturised biochemical sensing platforms, highly effective disease treatments and the shaping of biological processes to suit a particular application. Examples of possible applications include lab-on-a-chip devices that can quickly identify toxic biological agents and/or provide constant health monitoring. These devices could also include “nano-drug” [sic] delivery systems capable of administering personalised medical treatment to specific parts of the body, as required.

3.3.1.2 Analytics and Sensing

The study of complex biological and natural processes using computational tools has led to the development of mathematical models and abstract representations of these systems. Increased computational power and nature-inspired analytical tools will continue to rapidly develop. Language, behaviour and physiological pattern recognition may all be radically improved with the introduction of novel biometric algorithms from 2020 onwards. Advanced biometric applications may be increasingly sought in light of future security concerns from difficult-to-detect adversaries. Discrimination based on DNA pattern recognition could enable a new class of sensors. These might allow the development of methods and tools capable of chemically marking and identifying biological and chemical processes affected by specific DNA functions. Similar tools could be used to map higher-order brain functions governing human behaviour to their neurochemical signatures. Aspects of human cognition and social interactions could be predictable from 2030 onwards, if such developments are coupled with developments in applied sociology, complexity theory, and biometrics.

3.3.1.3 Biological augmentation and Human-Machine Interfaces

Ongoing developments in technologies that improve quality of life, extend life spans, advance human performance and serve to overcome the physical limitations of the human body are expected to continue. In the more immediate future, from 2015, it is expected that highly resilient and flexible displays will extend human vision and perception in a range of demanding applications, such as aircraft control. Immersive simulation environments may also benefit. Artificial implants that enable additional sensory abilities in people of limited hearing or sight are expected to become smaller, completely biocompatible and will not require replacing. Such close integration of technology with the human body is expected to move on from providing additional sensory awareness in people with disabilities to maturing into brain-machine interfaces (BMI) by 2030. BMI could be used in conjunction with advances in wearable computers and input devices – from 2020, voice and gesture recognition and optical sensing are expected to become a standard way of communicating intent to computing and autonomous systems.

In the broader realm of human augmentation, an entirely new class of technologies may be available between 2020 and 2060. Developments in targeted drugs design are very likely to provide new classes of performance-enhancing medication. These are likely to evolve from the near-future medical needs of ageing societies where cognitive impairments are common. Drugs that improve cognition are likely to have significant commercial and social imperatives and may evolve into products which could improve memory, intelligence, endurance and overall physical performance. Similar classes of drugs could lead to breakthroughs in treating previously untreatable brain conditions. From 2020, skin, tissue and organ growth may provide donor-less body parts. Nanotechnology may ultimately offer the framework necessary for the growth of higher complexity organs on nanopatterened scaffolds beyond 2020.

3.3.1.4 Biomimetics and synthetic biology

A whole range of biological applications could be used to extend human abilities beyond the current limitations of human physiology. Driven by a commercial need to provide greater quality of life to ageing populations, these technologies could extend lifespans and physical and mental abilities.

The integration of biomimetic implants would allow for artificial systems to be seamlessly integrated with human bodies. Examples already exist of crude control systems used to control the flight of insects. As similar technologies mature, they are likely to become smaller, more portable and more reliable leading to possible uses in medicine, aerospace and household applications. Other applications could include: biomimetic materials used in organ repair, or the development of autonomous aerial vehicles that are indistinguishable from insects. Another important aspect of biomimicry will be to encapsulate the cognitive capabilities of human reasoning in artificial systems.

Autonomous reasoning and learning is a less physical example of biomimetics that by 2035 could result in autonomous decision making systems capable of reasoning under conditions of great uncertainty. Increasing demand for machines capable of making unassisted decisions under uncertain conditions may present difficulties in manufacturing these systems in sufficient quantities as many of these could depend on (presently) difficult to manufacture nanotechnologies.

Biofactories and biological substrates may allow the mass production of electronics, synthetic biochemicals and nanostructures essential to the miniaturised technologies required by biomimetic systems. Synthetic biology could be used to produce new materials and enable new energy sources. Large-scale manufacture of biochemicals may be developed in response to the growing need to find replacements for fossil fuels. Reproduction of artificial photosynthesis to create a new generation of solar cells might occur between 2020 and 2030. Biomimicry in materials science could result in new generations of cheap, easily produced high-strength materials. For example, by studying microbial interactions, researchers have been able to use bacteria to produce spider silk proteins in quantities two orders of magnitude greater over what was possible before. Elsewhere, genetically engineered silk-worms were used to mass produce spider-silk with biological spinning, achieving significant manufacturing improvements. Further out, beyond 2020 and subject to environmental conditions (such as public perceptions and ethics), programmable organisms might achieve specific functional tasks on a molecular level. Bioengineered chemicals based on synthetic bioactive peptides could also used to elicit specific cellular responses in human metabolisms to effect behavioural changes. The UK MoD have indicated these could have unnamed, but significant defence applications [43]. Applications of synthetic biology and future neuroscience developments could lead to breakthrough understandings of human cognition and their modelling in computing domains – with significant implications for automatic pattern recognition potentially superior to human abilities. This would have far-reaching consequences for autonomous systems, data analysis techniques and sensor technologies.

3.3.2 Materials and Manufacturing

3.3.2.1 Materials

Developments in materials technology have traditionally been an enabler for other technology areas such as nanotechnology, vehicles, space, ICT and energy technologies. Future developments in materials are expected to produce cross-disciplinary effects across the same areas. The manipulation of the physical properties of these future materials is expected to fall within the purview of nanotechnology and it is nanotechnology that is expected to provide the most significant advances to materials development in the coming decades. This new family of nano-materials would enable multifunctional properties in materials specifically tailored for a particular use. These developments might arise from biomedical requirements in organ repair and tissue engineering, or engineering and computing challenges of the future. New generations of nano-materials may specifically develop for aerospace applications so that by 2020 it could be possible to apply high-performance coatings, possibly improving low observability, material strength and environmental resistance just by “painting” existing aircraft structures. De-icing composites capable of intrinsically impeding ice-crystal growth could become a reality by

2030. Self-healing materials could revolutionise most material applications by enabling self-repair and maintenance within existing structures. Nanoscale electronic applications such as programmable materials or high-capacity semiconductors could radically affect computing architectures from 2020 onwards. These could give rise to subsequent families of complex electronic materials such as smart fabrics, which from 2020 or 2030 onwards may embed power sources, personal protection and mechanical actuators within wearable and highly flexible surfaces. Developments in optoelectronic and photonic materials may produce materials that are semi or fully transparent across many frequencies (optical, RF and/or IR) with a possibility of disruptive developments in EO transparency from 2030 onwards. Carbon nanotubes (CNTs) may see their use as structural members in high-performing applications such as morphing wings, intense radiation environments, and space elevators beyond 2020. More immediate applications of CNTs might lead to weight reductions of vehicles or as safe, room temperature energy storage devices for hydrogen fuels. CNTs might also enable electron tunnelling effects on macroscopic scales in nanowires that are lightweight, near-superconducting at room temperature and have very high thermal conductivity. In the more distant future, between 2030 and 2060, generations of quantum materials might naturally evolve from nano-electronic applications. These would enable the exploitation of macroscopic effects of quantum coherence for quantum computing, use of high temperature superconductivity to revolutionise electrical systems and provide materials for low-temperature (high efficiency) high-energy lasers.

3.3.3 Manufacturing

Advances in manufacturing techniques could allow future technologies to be developed and produced with greater ability. The ability to mass-produce these nanomaterials will depend on improvements to large-scale nanoscale fabrication which may occur from 2020 onwards. Programmable manufacturing techniques could, from 2020, allow rapid multi-functional design and growth of new structures, materials and products using self-assembling nano-bricks. Similar applications for medical use might produce self-assembling quantum materials for neurological repair and regeneration. Synthetic biology and in particular, biomimetics are likely lead to the development of new generations of biological materials and manufacturing techniques. These could be used to develop low-cost and highly functional brain-machine interfaces, leading to applications to human performance augmentation technologies such as cognition enhancing drugs and bio-compatible electronics.

Traditional manufacturing technology may also benefit from the use of programmable materials and structures to increase the precision and speed of automated manufacturing processes using information technology and robotics. Consumer demand for 3D printing could lead to improvements in such technologies that could, over the next 10 years, allow the creation of complex, multi-layered surfaces for use in aerospace components, electronics or human organs and tissue. Biotechnology developments between 2020 and 2030 may open up new capabilities in manufacturing using DNA replication and genetic coding to enable molecular-level manufacture and design. It is expected that a wide adoption of 3D printing technologies would have disruptive effects to distributed manufacture, possibly negating the effects of economies of scale in traditional manufacturing.

Environmental drivers such as climate change and the rising costs of energy may force traditional manufacturing methods such as industrial chemistry into becoming more efficient. Quantum chemistry, may allow the use of highly predictive chemical models to design chemicals tailored to exact energy requirements and reaction rates, possibly enabling new generations of fuels and energetic materials. A shift towards green chemistry and green manufacturing, also driven by rising environmental concerns may stimulate developments in biomass manufacture, allowing biofuels to be developed more effectively. Should manufacturing operations in extreme environments such as space, deep ocean and polar regions become more commonplace, new micro-sensors and actuators for operating in harsh environments could be developed quickly. Future developments in Micro Electro-mechanical Systems (MEMS) and Nano Electro-mechanical Systems (NEMS), possibly occurring from 2020 onwards, would enable the use of MEMS for microfluidic actuators for bird-like micro-aerial vehicles (MAV) capable of generating lift in low-speed conditions.

3.3.4 Computing and Artificial Intelligence (AI)

3.3.4.1 Information processing and computing architectures

The socio-economic drivers behind the development of more powerful computing tools are expected to continue. Given the high likelihood of the generation of large data quantities and the need to perform real-time analyses, several technologies may be developed to meet these needs. New algorithms and techniques would improve autonomous complex pattern searches, track logistics and perform automated trading in the near term. Such developments could evolve into more sophisticated algorithms for use in AI systems. The growth in the use and application of internet applications may result in further developments of the semantic web which would be machine readable and more easily accessible with human-machine interfaces. The need for portability and ubiquitous computing may lead to rapid developments in Magnetoresistive Random-access Memory (MRAM) and spintronic architectures[10] that could enable high data densities and miniaturised microwave-capable communications at nanometer scales from 2020 onwards. These architectures could provide enabling advances for quantum computing and alternatives to transistors in future neuromorphic computer platforms capable of human-like reasoning and pattern recognition by 2040. Possible commercial requirements of dealing with large customer bases and populations may lead to new techniques being developed in computational sociology and behaviour prediction out to 2030. These tools could be used to estimate and eventually predict mass human behaviour based on visible social patterns.

With the possibility of increased intensity in weather events as a consequence of climate change, the need to have accurate and predictive weather models may stimulate rapid developments in computational modelling, multisensory networks and massive analytics.

---

[10] Spintronics manipulates electrons' spins and its most notable success has been enabling high data storage densities in hard drives using a spintronic effect of Giant Magnetoresistance (GMR). GMR was experimentally observed in 1988 and was first used as HDD technology in 1997 – causing data densities to increase two orders of magnitude over the next 10 years. Other spintronic applications have included switching and re-routing light in information processing and optical communications; or for processing radio signals in mobile phones [44].

Such pervasively networked sensing technologies could be used to monitor and predict the weather, complex social patterns, or to provide adaptive and realistic training environments. In medicine, data could be gathered from combinations of embedded sensors that would stimulate developments in bioinformatics and related algorithms dealing with the prediction of biological, rather than weather processes. Both these systems would require enabling advances in secure and flexible ad-hoc networks that are capable of network polymorphism under a variety of physical and cyber threats.

Some of the most disruptive changes in information processing could arise from developments in alternative computing architectures. Understandably, any major breakthroughs in quantum computing would radically change the way computers would be used. With orders of magnitude increases in speed through massively parallel processing, traditional cryptography methods may be rendered insecure and obsolete with quantum cryptography taking its place. This could challenge data security, an area already under increasing pressure from cyber threats. Complex pattern recognition could become possible, enabling the creation of artificial intelligence and human-like artificial reasoning. Such breakthroughs may occur between 2020 and 2060. Recent developments in biochemical computing have shown that organic computers are possible, based on bioinformatics[11] applied to the chemical interactions of protein chains. Such systems could self-repair, be self-sustaining and might be integrated with other (synthetic) biological organisms, effecting biochemical changes and the regulation of body and behavioural functions through embedded DNA computing.

3.3.4.2 AI [12]

As computing becomes ubiquitous and driven by developments in massive analytics and data processing, the creation of software, tools and algorithms that ease human machine interactions in everyday and specialised situations will occur. Examples of rudimentary AI already exist, such as in consumer software, industrial hardware and aerospace systems. More complex AI systems may first appear in 2020 as autonomous systems and sensing platforms in the form of self-organising and evolving software capable of pattern recognition and learning within changing environments. As they become more sophisticated, security and defence requirements could lead to autonomous agents that would act against cyber threats or would be capable of fulfilling human intent, rather than being controlled or directed by human operators. Creative applications in intelligence gathering, surveillance and reconnaissance in cyber environments could be possible from 2025. An example application is a concept from USAF Air University [47] of a "cyberspace UAV" – a software agent that adapts to cyber threats to conduct intelligence, surveillance and reconnaissance (ISR) operations while also being able to provide support to cyber assets damaged by hostile activities. More complex AI applications such as autonomous reasoning and the ability to make decision-quality judgements based on perception are often envisaged to be able to outperform human cognition in terms of speed, capacity and

---

[11] Bioinformatics involves the application and design of computer algorithms to solve biochemical problems. The applications of bioinformatics extend to many fields, including: genome assembly, protein structure interactions, and the prediction of gene expression [45].

[12] Artificial Intelligence (AI): "It is the science and engineering of making intelligent machines, especially intelligent computer programs." [46]

accuracy. These systems are not expected to be developed before 2030, although there is an expectation they should be a reality by 2040. Robotic decision making that could be trusted by human operators to carry out decision-critical tasks will, in addition to technical challenges, require validation and the establishment of validation and verification frameworks for AI-enabled systems, which could delay or limit AI technology applications.

3.3.4.3 Simulation and training

Future learning environments are expected to make use of computing advances in establishing immersive, massively multiplayer simulation environments. Systems such as self-organising networks could aid information management and prioritisation. Economic globalisation and global knowledge circulation could drive the uptake and development of immersive collaboration tools with future systems appearing by 2020. Consumer demand for social and mobile computing might create technologies that would add to collaborative and problem-solving tools for use in future training applications. As collaborative tools improve, complex and flexible training environments would become possible. These systems might use intelligent agents, real-world data and social modelling to virtualise complex cultural and social environments. Future trainees might, between 2015 and 2030, use future human-machine interfaces in these training environments to experience realistic and highly adaptive virtual engagements. Future combat training systems might become integrated with such virtual synthetic environments, offering adaptive training, when required.

3.3.5 Communications and Sensing

3.3.5.1 Sensing and Navigation

Development of sensors and sensing tools will continue to be driven by security and defence requirements to enhance situational awareness. Commercial applications of modern vehicle routing systems are already using networked geolocators to generate geo-temporal data, collected by consumer devices such as mobile phones, enabling real-time traffic updates and enhanced routing. Future sensing systems are expected to increase connectivity, offering pervasive and real-time monitoring of all domains including extreme environments, such as deep sea and space. Enabling advances in sensing platforms and devices may also include significant breakthroughs in miniaturisation such that MEMS would evolve into viable NEMS systems. Major breakthroughs in NEMS "smart dust" sensing with integrated power and communications will possibly appear by 2040. From 2020, however, there may be MEMS use in miniaturised radar systems for Uninhabited Aerial Systems (UAS) and/or Uninhabited Combat Aerial Vehicles (UCAV).

Specific technology requirements of future sensors will depend on their application domain. The majority of future sensor technology is expected to be driven by security and defence requirements. Future detection systems are likely to include hyperspectral, terahertz and biochemical sensors used in stand-off substance detection. The technical complexity of these systems depends on their effective ranges; future generations of detectors for hazardous substances such as explosives or CBRN threats may appear between 2015 and 2030, with shortest-ranged systems appearing first. Similar systems could allow the detection of specific molecular signatures.

Positioning, Navigation and Timing (PNT) devices such as atomic clocks could also undergo significant miniaturisation so that a breakthrough in portable, micro atomic clocks or cold-laser interferometric devices might be possible by 2030. Quantum scale electronics could be used to develop miniaturised PNT systems in the future. Such developments would enable highly precise and resilient navigation and targeting systems.

3.3.5.2 Secure Communications

As technology is expected to become increasingly networked, with everyday devices becoming part of the internet of things[13] and with human interactions becoming progressively more internet-based, the need for information and data security is expected to grow. Cyber-threats could become a significant concern in the future security landscape, which could further increase developments in secure communications technologies. Consequently, secure wireless communications links would enable the use of pervasive sensor networks in mission-critical situations. Improvements to RF technologies and encryption methods would provide early enablers to these systems. Future systems could also make use of network polymorphism technologies from 2020 onwards to create frequency-agile and adaptive[14] communications links that would change network topology in response to attempted intrusions. Subsequent advances to these technologies could add AI technologies to secure networks which could include automated vulnerability assessments and reactions, allowing for operational efficiency under ongoing cyber-attacks. New communications platforms that are intrinsically safer than traditional RF-based methods could be realised by 2030. These might include laser-based systems. However, significant developments in quantum technologies would be required to enable high bandwidth, secure quantum-encrypted laser communications in congested environments through the lower atmosphere. Recent advances in quantum encryption on communication packets being transmitted through the atmosphere using lasers have shown such technologies to be feasible but at low data rates and limited distances. Similar laser systems might be combined with future vehicle technologies such as high-altitude airships that by 2030 might be used as near-space communications and sensing relays with secure laser communications capabilities. In the mean time, there are numerous laser communications demonstrators that allow for high bandwith, albeit less secure long-distance laser communications. The US Naval Research Laboratory (NRL) and NASA, for example have suggested inexpensive technologies that can be used to employ long-range laser communications to orbiting satellites [50], increasing communications bandwidths over traditional RF links by several orders of magnitude and providing reductions in power consumption by a factor of 50.

---

[13] The internet of things can be thought of as a “global network connecting any smart object”. Everyday objects could be made smarter by attaching RFID chips, GPS sensors, accelerometers, thermocouples and communications devices that broadcast that machine’s state out to the internet.

[14] Frequency agile communications systems have been developed. “Cognitive” or software-defined radios, for example are seen as offering 20,000 times the efficiency over spectrum assigned communications. The most recent technologies can sense unused radio bands (from 100MHz to 7.5GHz) and switch large quantities of data (approx 400MB/s) between different frequencies without interruption [48]. Some experts have placed an upper limit to the commercial availability of these as 10 years from now (approx 2020) [49],with defence applications likely appearing much sooner.

3.3.6 Energy

3.3.6.1 Directed Energy

Future applications and developments of energy-related technologies will likely include directed energy systems[15]. Because of the expectation that future security will become less permissive, directed energy technology is likely to mature into fielded military capabilities. This is because Directed Energy Weapons (DEW) systems are regarded as having significant advantages in terms of speed, logistics, lethality and precision against many targets [26, 57-59]. Military applications of directed energy systems are expected to remain the most important drivers for directed energy technologies, although power delivery systems based on microwaves or lasers could also generate some breakthroughs. The near term is likely to see a combination of solid state and fibre laser technology used to provide the necessary power densities in small packages. Lower-energy options such as short-range laser defence with kilowatt class laser systems are expected to become operationally viable first[16]. Such systems would be able to incorporate sophisticated target tracking technologies to defeat multiple air-threats quickly. The use of very short wavelength femtolasers which have self focussing abilities may help alleviate the effects of atmospheric attenuation over large distances with such improvements to laser systems expected after 2025. To increase the effective ranges of laser-based systems, further advances to materials and energy storage technologies will be required. Extremely portable systems such as a 300kW airborne laser capable of autonomous self-defence and directed strike capabilities are not expected to occur before 2030, when improvements in materials technology could enable the high energy densities required for such applications. Non-lethal directed energy delivery methods such as microwave and RF energy have already been developed in response to slightly different requirements, including civilian crowd control using microwave beaming; and electronic warfare. Delivery of electronic attack capable of selective disruptions to electronics may be commonly available before 2040.

3.3.6.2 Energy Generation and Storage

A number of changes to the physical environment may require significant improvements to energy generation, storage and delivery technologies. Environmental concerns and the perceived need to look for non-fossil fuel based energy supplies have already stimulated developments in alternative fuels and energy generation technologies. Portability and miniaturisation requirements arising from consumer electronics and military applications may lead to rapid improvements in energy storage technologies. These energy requirements are driving a range of technologies that are summarised as follows:

- Carbon nanotubes could enable new generations of hydrogen fuel cells that are substantially safer and easier to manufacture as the hydrogen fuel is captured and stored within these new nano-structures.

---

[15] Directed energy systems include all technologies which use non-projectile methods to deliver power, such as: laser or microwave systems (electromagnetic waves); particle beams that accelerate particles to near-light (relativistic) speeds; and acoustic systems.

[16] The DARPA HELLADS program aims to develop a 150kW airborne tactical laser aimed at defeating RAM threats. As of June 2011, one of the two requisite laser modules had been built. DARPA hopes to have the technology transition into an airborne demonstrator sometime after 2013 [51].

- Large scale applications of supercapacitors by 2020 could enable future vehicle systems with large peak power requirements or applications where high energy densities are required over short periods of time, such as directed energy weapons.
- Improvements to manufacturing processes may allow mass production of synthetic high-energy materials such as biofuels and synthetic fuels from commonly available raw ingredients or biomass.
- Rugged and deployable biorefineries that generate energy from waste could be realised sometime after 2025.
- Fourth generation fission reactors that produce safer and lower quantities of radioactive waste are unlikely to appear before 2020.
- An operational fusion reactor with sustained energy generation could be operational by 2030; however, due to the need for a technological breakthrough to move beyond experimental nuclear fusion reactors, it is unlikely that operationally viable energy generation through sustained fusion will occur before 2040.

More esoteric developments in energy generation could include the creation of micro- and nano-reactors based on highly efficient biochemical processes of living cells. In sufficient quantities, these could provide highly efficient energy generation to a synthetic bio-machine or to platforms that are small and require low weight (such as aerial vehicles).

3.3.7 Vehicles

3.3.7.1 Propulsion

Aerospace technologies in particular, are seen as relying on multiple cross-domain technologies. The results of this analysis suggest a diverse range of technologies is dependant on advances in future space and aircraft platforms. These are seen as being primarily driven by military and commercial needs for efficiency, speed and reliability. For example, future propulsion systems are expected to develop in response to high efficiency and low fuel consumption requirements. The USAF has identified the need for alternate fuels and evolutionary changes to jet engine technologies that would lead to improved efficiency jet turbine engines. Also, according to USAF, as the need for high speed military engagements increases, operations in supersonic and hypersonic flight are expected to increase [18]. An analysis of the timeframes for the F2T2EA[17] of a time-sensitive target (TST) suggests that the use of hypersonics during the engagement phase can significantly increase stand-off ranges. Further, the use of hypersonic penetrators provides significant increases to penetration depths (factor of 5 or more) against hardened targets. Platform survivability is likewise increased for high-speed/altitude platforms. Hypersonics are also seen by NASA as providing a more cost-effective way of delivering payload to Low-Earth Orbit (LEO) compared to rocket propulsion[18]. Hypersonic air-

---

[17] Find-Fix-Track-Target-Engage-Asess; this is a military term describing the entire targeting chain from detection (Find) to analysing the results of a target engagement (Asess).

[18] Third generation hypersonic propulsion research being conducted by NASA's Marshall Space Flight Center aims to use hypersonics to access LEO at a cost of $100 per lb of payload and low failure rates (10^{-6}).

breathing engines used in future aerospace vehicles would address these requirements for high speed but not without enabling advances in material technologies.

According to NASA, hypersonic reusable space-access systems fall into two categories: rocket-based combined cycle (RBCC) or turbine-based (TBCC). Both use dual-mode scramjet[19] engines throughout the operating envelope, reaching speeds of Mach 12 to 15. A similar distinction can be extended to hypersonic applications of atmospheric vehicles. The USAF has suggested limiting hypersonic speeds to Mach 6 as a way of avoiding the difficulties of dealing with the aerothermal effects at higher operating speeds. They have identified RBCC as a technology viable within a 2030 timeframe for aircraft use on important missions: rapid and standoff strike of TST; and ISR. For space access, the Single Stage to Orbit (SSTO) design is considered the most cost-effective reusable space-access system [53].

While it is estimated that aircraft are unlikely to make use of hypersonic propulsion systems before 2030, cruise missiles are expected to use hypersonic propulsion first with subsequent additions like advanced PNT technologies for increased precision and jam resistance extending their capabilities over the lifetime of the missile.

A passenger aircraft capable of popping in and out of the atmosphere while cruising at hypersonic speeds is tentatively viable within the 2050 timeframe. Such concepts use the rarefied atmosphere of near-space to reduce the effects of aerothermal heating and fuel consumption when compared with continuous operation scramjet engines. Meanwhile, steady improvements to fuels, nozzles, health monitoring systems, MEMS flow control devices and specialised materials may create steadily improving, high-efficiency turbine engines before a new generation of propulsion technology is invented. Speculative concepts, that may be viable from 2050 and beyond suggest non-chemical sources of energy to fuel propulsion systems of the future. Hypersonic engines that use the magneto hydrodynamic effects of plasma to cool hypersonic propulsion systems and/or generate electricity may be developed. Other concepts include using microwaves or nuclear power instead of chemical propellants.

3.3.7.2 Configurations

Commercial and military requirements emphasising efficiency, speed and reliability will drive what future generations of vehicles will look like. The most significant changes may be in future aircraft configurations. More efficient platforms, such as blended or hybrid wing-body aircraft could replace traditional wing-tail-fuselage configurations by 2030; with designs that need highly augmented future control systems due to their inherent instability. These configurations might provide a common aerospace platform for use in diverse applications where fuel efficiency is a major consideration. MEMS flow control devices could be used to eliminate control surfaces and substantially reduce drag and

---

[19] In a dual-mode scramjet system, the engine functions as a dual-mode ramjet (inlet flow is supersonic but combustion occurring at subsonic speeds) between Mach 3 and 6. At speeds greater than approximately Mach 6, the engine operates as a dual-mode scramjet (inlet flow and combustion occurring at supersonic speeds) [52]. The difference between RBCC and TBCC systems is in low speed operation – the rocket-based system uses a rocket engine to accelerate at low speeds, while the TBCC uses a turbine engine for this purpose.

radar signatures. Another possibility could use high altitude long endurance platforms (HALE) as persistent ISR and communications relay systems in areas where geographical terrain features limit radio coverage. The USAF has identified high altitude airships (HAA) which could also be used to provide similarly persistent, near-space ISR capabilities at a fraction of the cost of a LEO or a Geosynchronous Orbit (GEO) satellite[20]. It is also expected that airships could be used as low-cost, heavy air transport options that would be faster and more capable than traditional sea vessels. Future long endurance aircraft applications, such as loitering HALE/HAA concepts that are capable of staying aloft for months and years, will be exposed to the harsh environment of near-space for extended periods of time. This would require significant improvements to fabrics or outer shell materials such that they are heat and radiation resistant, lightweight and multifunctional. Additionally, solar panels and high energy-density storage and health monitoring technologies would be required to support such future HALE/HAA systems, making such complex systems unavailable before 2030.

Other forecast air vehicle configuration concepts include:

- New commercial, transatmospheric aircraft and reusable access to space launch arising from the use of hypersonic propulsion systems.
- USAF has suggested that military requirements of low observability and high-speed could result in the operational availability of a supersonic global bombing/strike platform from 2037 onwards.
- Vehicles that are networked and capable of self-organisation (swarming) through shared sensory networks could take until 2040 to develop.
- Very speculative[21] near-space vehicles that use microwave power beaming technologies to remain aloft at altitudes exceeding 70km.

3.3.7.3 Unmanned and Autonomous Systems

Moving from human-operated vehicles to semi or fully autonomous operations is expected to be a feature of aerospace systems in particular. Further developments in the use of autonomous vehicles for space and planetary missions are expected to continue and to improve autonomous systems and sensing platforms. While strong ethical opposition to the use of autonomous vehicles may prevent extensive non-military use of such technologies for unmanned passenger vehicles, there is a strong suggestion that autonomy will be a feature of the future of aerospace.

In addition to the enabling developments in communications, sensing and computing technologies (including AI), military operational requirements are expected to be a significant driver for future unmanned and autonomous systems. This will partly be in response to an increasing likelihood of military operations in highly contested environments and the social sensitivities attached to the loss of life of service personnel –

---

[20] The HALE-D concept from Lockheed Martin and DARPA's ISIS program are both looking at developing such capabilities.

[21] It is presently still considered a more costly choice to continuously beam energy to a near-space craft than use buoyancy on an HAA to keep it aloft [54].

cheap unmanned or autonomous systems can more readily be considered expendable. Autonomous targeting and engagement technologies may shrink decision cycles to levels below what is achievable by the human operator. The development of these will depend on significant advances to materials, computing, artificial intelligence, sensor and energy technologies, as well as overcoming significant ethical concerns and will be unlikely to exist before 2040. Other military operational requirements will influence on the future of unmanned and autonomous systems development. Unmanned or autonomous helper vehicles could accompany manned aircraft and provide support for operations where the main vehicle is unwilling or unable to engage. These UAS could self-diagnose or repair themselves, conduct ISR, Suppression of Enemy Air Defences (SEAD), counter-air, act as C2 nodes and extend the existing weapons payload on board the main aircraft. These systems could also be configured to act as transport or refuelling platforms or provide EW support.

The need for survivable, agile and resilient platforms may be filled by fractionated systems by 2030. These systems may be able to fly in groups where individual elements provide composable[22] capabilities. Low observability in such systems could be achieved through the combination of low speed, low weight and reduced RF signatures for increased survivability, but because of their redundancy, they could also be expendable.

Typical non-military applications of future autonomous systems include near-term (2015-2020) visions of automated transport networks responding to congested urban environments where traffic flows are autonomously monitored in real time to provide networked vehicles with information on optimal speeds and paths. Distant applications of such systems could bypass human operators of these vehicles. Ultimately, there is an expectation that autonomous systems will possess sufficient autonomy to carry out human intent without being directly controlled by a human operator.

3.3.8 Space

3.3.8.1 Guidance and Control

The use of space-based assets is seen as being contingent on achieving safe space access and maintaining safety in orbit. One of the greatest threats to space systems is the increasing threat of orbital debris. NASA has already suggested that a near-term energy and cost-efficient way of mitigating the threat from orbital debris would be to use a 5kW laser to steer the debris away and onto a collision-free orbit [55]. Another major risk to space systems is the possibility of militarisation of space through the introduction of space-based weapons systems and anti-satellite technologies. The ability to mitigate both risks depends on the ability to detect, monitor and predict orbital paths of space systems. Persistent space situational awareness (SSA) technologies and improved orbital prediction tools may be developed by 2030 in response to such needs. These could allow the level of tracking required for sufficiently advanced collision warning systems to enable rapid manoeuvring of existing assets out of harm's way. In addition to being able to track debris and systems the size of a picosatellite (0.1kg to 1kg), The USAF suggest that a complete

---

[22] Composable refers to the modular nature of using multiple inter-related satellites to ensure an always-on capability in space-based assets.

SSA system would also have spaceward sensing capabilities with EO/IR payload detection against space assets with unknown intent and/or weapons capabilities.

3.3.8.2 Configurations

Future space systems could offer applications whose use, once demonstrated, might become part of a new generation of space assets. Using future advances in air-breathing propulsion systems, space access could be made cheaper should two stage rocket-scramjet systems become viable. Contingent on advances in high temperature materials, health monitoring and autonomy, reusable air-breathing space access vehicles might become available by 2030 with significant improvements to fuel efficiency and overall payload delivery costs. Future technology developments could also result in satellites becoming smaller and more capable. By incorporating a modular architecture, these micro- or nano-satellites[23] would be capable of rapid reorganisation and reconstitution of damaged or failed systems within similar timeframes. They would be able to provide redundancy and survivability via fractionated system elements that could self-assemble into complex space platforms. While such systems could develop in response to non-military requirements for safe and reliable space operations, should weaponisation of space occur, an inexpensive delivery system capable of striking global targets with orbital speeds may be the first such asset to be developed. Such a system could be based on multiple satellite launchers with tungsten projectiles whose kinetic energy would be sufficient to destroy deeply buried and high-value targets globally and within minutes[24]. Less speculative space weapons include future ASAT technology – both ground and space based. While kinetic ASAT technology has existed since the 1960s[25], the use of directed energy (DE) effectors is relatively recent. Current technologies allow ground-based lasers to effectively blind other satellites[26]. Future ASAT systems might move beyond ground based approaches to DEW effectors that kill, rather than blind. In the long term, orbiting small satellites could potentially be used as weapons.

---

[23] Microsatellites are a class of satellites with a mass of 100kg of less. The US Defense Area Technology Plan identified microsatellite Autonomous Proximity Operations (APOs) as "[To be able to] conduct missions such as diagnostic inspection of malfunctioning satellites through autonomous guidance, rendezvous, and even docking techniques" [56]. Nanosatellites are smaller still, with masses typically between 1kg and 10kg.

[24] The USAF referred to this concept as "hypervelocity rod bundles" and notes them for being able to strike ground targets globally with precision. Their 2003 report estimated the capability as viable by 2015 [57]. In addition to the hypothesised effects, some studies have shown that such weapons may be unfeasible and that USAF had not worked towards developing such a capability [56].

[25] US' Program 437 operated between 1964 and early 1970s consisted of a ballistic missile with a 1.4MT nuclear warhead. The USSR developed a "satellite destroyer" during similar timeframes – a weapon that would fire a weapon in the target's orbit, while in sufficient proximity to disable the target satellite [58].

[26] In 1997, the US tested a dazzling laser against one of their own satellites [59] (page 58).

4. Discussions/Conclusion

4.1 Results

This scoping study has four main outcomes:

1. A summary of the most pertinent environmental trends and drivers shaping the development of future technologies (Chapter 3.1).
2. A tabulated list of 100 future technology applications, descriptions of underlying technology concepts; cross-disciplinary influences of these concepts on alternate application areas; and expected maturation timeframes (Chapter 3.2 and Appendix B).
3. A narrative that combines the analyses of the environmental trends and drivers with the list of 100 future technology application areas into a story-like brief of future technology options (Chapter 3.3).
4. A literature review method and coding scheme that can quickly extract information from a very diverse and large volume of reference material (Chapter 2).

Information about the environmental trends and drivers shaping the development of future technologies out to 2060 provided this study with a context for future technological change. This contextual background should provide a representative example of future environmental challenges and as such may help long-term planners appreciate which future trends may herald the uptake or development of new technologies.

The prioritised list of 100 future technology applications illustrates which future technology applications appear to be the most popular (mainstream). The list gives the reader the ability to discern between the “traditional” and the “unorthodox” future technologies, with respect to open literature perspectives. The prioritised list of future technology areas (Table 3-3, Chapter 3.2.2) can be used to identify technology application areas that are under-represented. Where appropriate, further studies could examine the relevance of these technologies for defence applications.

The persistency ratings developed here, help the reader appreciate the pervasiveness in the literature of certain technologies over others. High persistence scores are a reflection of the prevailing consensus on particular patterns of future change and the broad application areas the technology may have. Low persistence scores reflect niche application areas and interests. Neither is meant to imply how likely a future technology is to materialise. Potentially any number of these technologies could become commercially and operationally available by 2030 and beyond. The scores do not reflect the likelihood of emergence of a technology and tend more to reflect the breadth of utility of the underlying technology concepts. For instance, one can see that military technologies tend to dominate the bottom-half of the table, with technologies that serve a single use case (such as weapons) or are very domain-specific (such as space technologies) appearing closer to the bottom. This distinction is important because it may help planners, who are looking to leverage dual-use technologies for defence and national-security outcomes, to invest into those areas that will have the greatest impacts across multiple technology application areas. They may choose to further investigate technologies that appear to serve non-military interests at first glance but actually have significant overlap with technology application areas for defence. To glean this level of insight for technologies analysed in this study, the reader should also refer to the accompanying data presented in the expanded table given in Appendix B.

The interplay between the environmental pull and technology push effects is important. The narrative of Chapter 3.3 tries to inform the reader about some of these intricacies in a way that maintains accessibility in light of the material's complexity. Each technology is described in terms of technical advances, postulated application areas and the environmental trends and drivers having a specific impact on its development. Environmental trends and drivers have been injected into the summarised findings on future technologies to describe, in broad strokes, the open literature's perspective on emerging and future technologies. This reduces the information-dense, tabulated findings on emerging end future technologies and the drivers for their uptake and development into a more holistic picture of future technology issues. Because of its story-like presentation, the narrative provides an alternative and accessible way for stakeholders to re-interpret the information that is found in other chapters. This narrative does not prioritise technologies in any way, leaving open the possibility to re-prioritise the technologies according to a different set of criteria.

The development of a method that enabled the consideration of both mainstream and unorthodox opinions was essential to the delivery of these results. The resulting diversity in opinion and the volume of data available to the analyst was significant. Without a structured method, this study, given its limited resources, would have been unable to consider the issues that were important in a consistent fashion. The coding scheme was developed to systematise the aggregation of data from the vast body of literature in an unbiased way. This method can be adapted for use on similar tasks involving large volumes of unstructured, qualitative information.

4.2 Limitations

Any interpretation of these outcomes should consider the study's principal limitations. These included the complexity of the problem; the choice of reference material; cultural bias introduced by source material; analytical biases experienced by the analyst; and the limitations of the coding method.

The main aim of this study was to improve the understanding of what technologies may be available in the 2030-2060 timeframes. Consequently, the emphasis on including the contextual backdrop affecting the development of future technology areas was small compared to the emphasis on collecting data for future technology concepts. This was demonstrated by not subjecting the information on the future trends and drivers to the methodical coding and information filtering process that data supporting future technologies was subject to. The data on environmental trends and drivers therefore offers a more limited perspective because the majority of the literature review focused on technological rather than environmental developments. Hence, the reported perspectives about future trends may vary substantially for different sets of sources not looked at here. It is also likely that including only the "reputable" sources captured only the mainstream perceptions of requirements pull effects on future technologies. Subsequent studies under this task may consider a wider set of alternate futures and their requirements pull effects on future technologies.

Changing the underlying source materials, could significantly alter the study's outcomes. For example, changing the source material to be less diverse and more military oriented, would change the persistency scores. The assumption here was that a diverse set of references should yield a sufficiently diverse overview of the pertinent technology issues; the validity of this assumption has not been tested and it is debatable whether this could be done due to the complexity of the problem. These persistency scores (P-scores) can thus only be used to rank mainstream ideas (high P-score) from unconventional ones (low P-score), for this particular set of source material.

Another limitation in the selection of the source material stems from using only expert opinion. It was assumed that expert opinion could ensure a more consistent quality standard at which all opinions could be equally valid. It is possible that non-expert futurists could have provided an even more diverse range of technology options, but at the expense of an increased variability in quality. This uncertainty may have required additional analytical effort to treat effectively. Therefore, a decision was made to discard non-expert speculation, at the expense of reducing the diversity in the collected opinion on future technologies.

A more obvious limitation arises from the fact that all of the reference material was written in English. While reports from international agencies such as the UN can be thought of as multi-cultural in authorship, the bulk of the collected information is likely to be biased for Western, English-speaking perspectives. The source materials dealing with China for example are mostly US analysts' interpretations of what the native Chinese sources had reported. The author had no visibility of an accessible, native Chinese perspective relevant to the study timeframes. Instead, for example, US analyses [38] of future Chinese defence needs were used to provide the relevant information. A translated Chinese report on future technologies [13] contained vague references to military technologies which echoed perceptions of Chinese security needs reported on in the US publication. This perspective could have skewed parts of the analysis that dealt with military technologies in particular, in favour of US perspectives. The effect of this cultural bias is very difficult to overcome, without access to a multi-lingual team of analysts.

During the course of this study, preferential attention was likely given to high-impact[27], disruptive and (subjectively) interesting topics[28]. The effects of both were reduced by relying on the coding scheme to prioritise the information. However, there will always be the risk that the reader's own interpretation of the results will be biased the same way and the information about the most persistent technologies that are presented here could be

---

[27] Sometimes referred to as sensationalist bias

[28] Sometimes referred to as cognitive bias

prioritised differently, according to their own set of requirements. This is partly why a narrative that does not take into account persistency is included as part of the analysis.

The medium–term horizon (10-20 years into the future) was predominantly considered when discussing future forecasts and application areas of future technologies. This was due to the greater selection of candidate sources whose studies related to a medium-term timeframe (examples of which are the UK Sigma and Delta Scans [28]). This could have had an effect of skewing the analysis towards less speculative, medium-term technologies.

While the coding method helped establish a rigorous framework for a consistent literature review, it is still a quickly developed simple tool. Risks in using the method arise from the following assumptions: that the assessment for whether sources are culturally similar or independent is based on the perceived country of origin; and, that two years was used as the limit on whether sources reporting from the same country were considered related.

4.3 Further work

This study identifies a broad range of topics that may be of interest for an ongoing horizon scanning study seeking to explore specific technology application areas. The results given here can indicate which areas may be worth exploring further. Consultation with RAAF stakeholders would identify any areas of interest out of the list presented here. Some of the trends and drivers identified here may also provide the context to appreciate the technical and operational implications of future technologies.

By way of improving the quality of the analysis, making use of automated tools for textual analysis may help identify early patterns in the data, without the subjective bias that can affect human-based analyses, especially when looking for candidate references. Performing this task manually requires the analyst to read and analyse every potential source - a task that is resource-intensive. Using an automated textual analysis tool would help identify specific sources early, expanding the diversity of the data, without wasting time analysing irrelevant information.

In conducting qualitative analyses on the selected sources, machine-assisted qualitative data analysis (QDA) tools can be particularly helpful. With analysts' input, these can track thematic patterns in the whole body of literature while assisting the analyst with establishing and applying coding frameworks to the data. Investigating the use of these tools may help develop a more consistent and reliable approach to conducting futures activities under the Air 07/036 task.

Acknowledgements

The author acknowledges the time and expertise provided by members of the Air 07/036 team that made important suggestions along the way: Dr Seng Boey, Dr Julia Chadwick, Mr Andrew Cruickshank and Ms Hal Harvey, with particular thanks to Dr Niem Tri and Dr Shane Dunn for their thorough reviews of the draft reports.

5. References

1. RAAF Museum. *Technology Hangar*. (2010) [Accessed 04/12/2012]; Available from: http://www.airforce.gov.au/raafmuseum/exhibitions/tech_hang.htm.
2. USAF. *Science of the Air Force*. [Accessed 04/12/2012]; Available from: http://www.airforce.com/learn-about/stem/#/science.
3. Berg, J., Nelson, F. and Rietz, T. (2003) Accuracy and forecast standard error of prediction markets. *Tippie College of Business Administration, University of Iowa*
4. Glenn, J. and Gordon, T. (2009) Futures research methodology- Version 3.0. *American Council for the United Nations University, Washington, DC*
5. Worlton, J. (1978) *Proceedings: AESOP Conference, volume 18: April 18-20, 1978, Amarillo, Texas*, US Dept. of Energy, Directorate of Administration, Office of Computer Services and Telecommunications
6. Chang, Y. S. and Baek, S. J. (2010) Limit to improvement: Myth or reality?: Empirical analysis of historical improvement on three technologies influential in the evolution of civilization. *Technological Forecasting and Social Change* **77** (5) 712-729
7. Devezas, T. and Corredine, J. (2002) The nonlinear dynamics of technoeconomic systems:: An informational interpretation. *Technological Forecasting and Social Change* **69** (4) 317-357
8. Fleischer, T., Decker, M. and Fiedeler, U. (2005) Assessing emerging technologies--Methodological challenges and the case of nanotechnologies. *Technological Forecasting and Social Change* **72** (9) 1112-1121
9. Dortmans, P. J., Curtis, N. J. and Defence Science and Technology Organisation (Australia). Land Operations Division (2004) *Towards an analytical framework for evaluating the impact of technology on future contexts*. Edinburgh, S. Aust., DSTO Systems Sciences Laboratory
10. Silberglitt, R., et al. (2006) The Global Technology Revolution 2020, In-Depth Analyses Bio. *Nano/Materials/Information Trends, Drivers, Barriers, and Social Implications*
11. Blass, E. (2003) Researching the future: method or madness? *Futures* **35** (10) 1041-1054
12. NASA. *Nasa Spinoff*. (2011) [Accessed 08/01/2013]; Available from: http://spinoff.nasa.gov/Spinoff2008/tech_benefits.html.
13. The State Council of China (2006) *Medium- and Long-term National Plan for Science and Technology Development 2006-2020.*
14. Rogers, S. (2010) Nasa budgets: US spending on space travel since 1958. In: *The Guardian*
15. Mays, N. and Pope, C. (1995) Qualitative research: rigour and qualitative research. *Bmj* **311** (6997) 109
16. Janasik, N., Honkela, T. and Bruun, H. (2009) Text Mining in Qualitative Research. *Organizational Research Methods* **12** (3) 436
17. Ministry of Defence (MoD) (2010) *Global Strategic Trends - Out to 2040*. DCDC
18. Chief Scientist (AF/ST) USAF (2010) *Technology Horizons: A Vision for Air Force Science & Technology During 2010-2030.*
19. Saka, A., Igami, M. and Kuwahara, T. (2010) Science Map 2008. *National Institute of Science and Technology Policy, NISTEP REPORT* **139**

20. Welch, E., Bretschneider, S. and Rohrbaugh, J. (1998) Accuracy of judgmental extrapolation of time series data: Characteristics, causes, and remediation strategies for forecasting. *International Journal of Forecasting* **14** (1) 95-110
21. Gnacadja, L. *Drought and desertification a growing threat to food security*. (2011) [Accessed 2011; Available from: http://www.trust.org/alertnet/news/drought-and-desertification-a-growing-threat-to-food-security-un-expert/.
22. Pezzullo, M., et al. (2009) *Defending Australia in the Asia Pacific century : Force 2030*. Canberra, Dept. of Defence
23. United Nations Educational Scientific and Cultural Organisation (UNESCO) and World Water Assessment Programme (WWAP) (2006) *The 2nd United Nations World Water Development Report: 'Water, a shared responsibility'*.
24. Birol, F. (2010) World Energy Outlook 2010.
25. European Foresight Monitoring Network (EFMN) (2010) *Key Technologies for France 2010: Foresight Brief No. 107*.
26. Canadian Armed Forces. Wing 17. and Chief of Force Development. (2010) *The future security environment, 2008-2030*. Ottawa, Chief of Force Development
27. De Schutter, O. (2010) Report submitted by the Special Rapporteur on the right to food. *United Nations Human Rights Council*
28. Outsights-Ipsos MORI. *The Sigma Scan*. (2006) [Accessed 2011; Available from: http://www.sigmascan.org/Live/.
29. Bushnell, D. M. (2001) Future Strategic Issues/Future Warfare [Circa 2025]. *EMERGING TECHNOLOGIES: Recommendations for Counter-Terrorism*
30. United Nations, Department of Economic and Social Affairs and Population division. *World Population to Exceed 9 Billion by 2050*. (2009) [Accessed; Available from: http://www.un.org/esa/population/publications/wpp2008/pressrelease.pdf.
31. Roudi, F. N. Population Trends and Challenges in the Middle East and North Africa. *Middle East* **2025** (2050) 65
32. Fuller, G. (2004) The youth crisis in Middle Eastern society. *Brief Paper. Clinton Township: Institute of Social Policy and Understanding*
33. United Nations, Department of Economic and Social Affairs and Population Division (2009) *World Population Ageing*.
34. United Nations, Department of Economic and Social Affairs and Population Division (2007) World Urbanization Prospects The 2007 Revision. 2
35. National Science Foundation (NSF) and Science Resources Statistics (SRS) (2010) Science & Engineering Indicators 2010. *USA: National Science Board*
36. Price Waterhourse Coopers (PwC) (2011) The accelerating shift of global economic power: challenges and opportunities.
37. Institute, S. I. P. R. *Sources and methods for SIPRI military expenditure data*. (2012) [Accessed 23/02/2012]; Available from: http://www.sipri.org/research/armaments/milex/resultoutput/sources_methods.
38. Office of the Secretary of Defense Washington DC (2009) Military Power of the People's Republic of China, 2009.
39. Griffis, A. (2010) *Predicting Future Capabilities of the People's Liberation Army Air Forces of China*. Storming Media.
40. Blanks, D., et al. (2009) *Future Capabilities and Technologies for the Air Force in 2030. Executive Summary*. Storming Media.

41. Futures Support Group (Canada) (2004) *ABCA Strategic Assessment of the Security Environment*. Ontario,
42. Berger, M. *NASA nanotechnology research into shape-shifting airplanes*. (2008) [Accessed 2012; Available from: http://www.nanowerk.com/spotlight/spotid=6067.php.
43. Ministry of Defence (MoD) (2006) *Defence Technology Strategy*.
44. Fert, A. (2008) The present and the future of spintronics. *Thin Solid Films* **517** (1) 2-5
45. Kari, L. and Rozenberg, G. (2008) The many facets of natural computing. *Communications of the ACM* **51** (10) 72-83
46. McCarthy, J. *What is Artificial Intelligence?*

"*Basic Questions*". (2007) [Accessed 2011; Available from: http://www-formal.stanford.edu/jmc/whatisai/node1.html.

47. Air University (US) Air Command and Staff College (2008) *Blue Horizons (BH) II 2008 Final Report*.
48. Badarinath, S. S. K. A. (2012) Frequency-hopping plan hits defence barricade: New tech can address scarcity of spectrum.
49. Talbot, D. *Frequency-Hopping Radio Wastes Less Spectrum*. Technology Review. (2012) [Accessed; Available from: http://www.technologyreview.com/printer_friendly_article.aspx?id=40586.
50. Marshall, W. (2012) Satellite Laser Communications on the Cheap In: *NASA Quantum Future Technologies Conference,* Moffett Field, CA, USA: 17.01.2012
51. DARPA. *Compact High-Power Laser Program Completes Key Milestone* (2011) [Accessed 2012; Available from: http://www.darpa.mil/NewsEvents/Releases/2011/2011/06/30_COMPACT_HIGH-POWER_LASER_PROGRAM_COMPLETES_KEY_MILESTONE.aspx.
52. Van Wie, D. M., D Alessio, S. M. and White, M. E. (2005) hypersonic Airbreathing propulsion. *Johns Hopkins APL technical digest* **26** (4) 430-437
53. Drummond, P., Bouchez, M. and McClinton, C. R. OVERVIEW OF NATO BACKGROUND ON SCRAMJET TECHNOLOGY.
54. Young, M., Keith, S. and Pancotti, A. (2009) *An Overview of Advanced Concepts for Near-Space Systems*. DTIC Document
55. Mason, J., et al. (2011) Orbital Debris-Debris Collision Avoidance. *Advances in Space Research*
56. Hitchens, T., Katz-Hyman, M. and Lewis, J. (2006) US SPACE WEAPONS: Big Intentions, Little Focus. *NONPROLIFERATION REVIEW* **13** (1) 35
57. United States Air Force (USAF) (2004) The US Air Force Transformation Flight Plan. *HQ USAF/XPXC, GPO*
58. Day, D. *Blunt arrows: the limited utility of ASATs*. (2005) [Accessed 2011; Available from: http://www.thespacereview.com/article/388/1.
59. DeBlois, B. M., et al. (2004) Space weapons: crossing the US Rubicon. *International Security* 50-84
60. United States Air Force (USAF) (2009) *United States Air Force Unmanned Aircraft Systems Flight Plan 2009–2047*. Washington, DC: Department of the Air Force.
61. NATO, Research and Technology Organisation (RTO) and TaskGroup062 (2010) *Assessment of Possible Disruptive Technologies for Defence and Security*. NATO Research and Technology Organisation (RTO)
62. National Institute of Science and Technology Policy (NISTEP). *Overview of research*. Research on Science and Technology Foresight. (2004) [Accessed 2010

04/10/2010]; Available from: http://www.nistep.go.jp/nistep/about/thema/themaA-e.html.

63. Bozkurt, A., GILMOUR, R. and Lal, A. (2009) Balloon-Assisted Flight of Radio-Controlled Insect Biobots. *IEEE transactions on biomedical engineering* **56** (9) 2305
64. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 474*. (2007) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/474/.
65. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 283*. (2010) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/283/.
66. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 461*. (2006) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/461/.
67. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 543*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/543/.
68. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 473*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/473/.
69. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 550*. (2009) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/550/.
70. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 521*. (2009) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/521/.
71. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 468*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/468/.
72. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 526*. (2006) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/526/.
73. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 530*. (2004) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/530/.
74. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 516*. (2010) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/516/.
75. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 464*. (2010) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/464/.
76. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 300*. (2009) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/300/.
77. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 429*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/429/.
78. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 514*. (2004) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/514/.
79. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 410: Growth of Evolutionary Psychology*. (2007) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/410/1/growth-of-evolutionary-psychology/.
80. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 477: The Brain Imaging Revolution in Psychology*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/477/1/the-brain-imaging-revolution-in-psychology/.
81. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 520: The Rise of Applied Sociology*. (2005) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/520/1/the-rise-of-applied-sociology/.

82. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 438*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/438/.
83. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 511: Growing Market for Lifestyle Drugs*. (2009) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/511/1/growing-market-for-lifestyle-drugs/.
84. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 287: The Extended Self - Better than Well*. (2006) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/287/1/the-extended-self-better-than-well/.
85. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 444: Designer Genes for Tomorrow's Children*. (2007) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/444/1/designer-genes-for-tomorrows-children/.
86. Ministry of Defence (MoD). *Emerging Technologies*. (2010) [Accessed 2010 05/01/2011]; Available from: http://www.science.mod.uk/strategy/dtplan/technologies_default.aspx.
87. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 512*. (2005) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/512/.
88. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 302*. (2007) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/302/.
89. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 417*. (2007) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/417/.
90. Koo, H. J., et al. (2010) Aqueous soft matter based photovoltaic devices. *J. Mater. Chem.*
91. Teulé, F., et al. (2012) Silkworms transformed with chimeric silkworm/spider silk genes spin composite silk fibers with improved mechanical properties. *Proceedings of the National Academy of Sciences* **109** (3) 923-928
92. El-Fatatry, D. A. (2007) Defence Applications of Nanotechnology. *NATO Research and Technology Organisation (RTO)*
93. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 291*. (2006) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/291/.
94. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 463*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/463/.
95. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 527*. (2009) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/527/.
96. TechCast.org (2011) *Latest Technology Forecast Results*.
97. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 426*. (2011) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/426/.
98. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 443*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/443/.
99. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 478*. (2006) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/478/.
100. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 422*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/422/.
101. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 434*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/434/.

102. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 484*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/484/.
103. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 554*. (2009) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/554/.
104. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 439*. (2006) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/439/.
105. Ring, W. (2007) *Silicon Photonics: Challenges and Future*. OPTOELECTRONICS INDUSTRY DEVELOPMENT ASSOCIATION WASHINGTON DC
106. Intel (2010) Intel Milestone Confirms Light Beams Can Replace Electronic Signals for Future Computers. 27 July 2010
107. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 431*. (2007) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/431/.
108. R&DMag. *First commercial 3-D bio-printer makes human tissue and organs*. (2009) [Accessed 07/03/2011]; Available from: http://rdmag.com/New-To-Market/2009/12/New-to-Market-First-commercial-3-D-bio-printer-makes-human-tissue-and-organs/.
109. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 436*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/436/.
110. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 451*. (2006) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/451/.
111. Liu, F. and Maboudian, R. (2007) Silicon Carbide Micro/Nano-Systems for Extreme Environment.
112. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 297*. (2007) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/297/.
113. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 487*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/487/.
114. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 502*. (2010) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/502/.
115. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 517*. (2004) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/517/.
116. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 541*. (2005) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/541/.
117. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 535*. (2006) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/535/.
118. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 483*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/483/.
119. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 408*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/408/.
120. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 303*. (2009) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/303/.
121. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 533*. (2005) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/533/.
122. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 499*. (2007) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/499/.
123. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 545*. (2010) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/545/.

124. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 418*. (2007) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/418/.
125. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 296*. (2009) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/296/.
126. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 534*. (2005) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/534/.
127. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 578*. (2010) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/578/.
128. Yin, J., et al. (2012) Teleporting independent qubits through a 97 km free-space channel. *Arxiv preprint arXiv:1205.2024*
129. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 481*. (2006) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/481/.
130. WorldFutureSociety. *Outlook 2009*. (2011) [Accessed 2010; Available from: http://www.wfs.org/Forecasts_From_The_Futurist_Magazine.
131. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 442*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/442/.
132. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 459*. (2008) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/459/.
133. NATO, Research and Technology Organisation (RTO) and AVT Task Group 078 (2004) *Military/Aerospace MEMS Applications*. NATO
134. GlobalSecurity.org. *B-3 Long Range Strike Platform*. (2008) Updated 23/02/2008 [Accessed 07/02/2011]; Available from: http://www.globalsecurity.org/military/systems/aircraft/b-3.htm.
135. Walker, S. H. *FLUID DYNAMICS ENTERS THE 21ST CENTURY*. (2000) [Accessed 2010; Available from: http://www.aiaa.org/aerospace/Article.cfm?issuetocid=35&ArchiveIssueID=7.
136. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 482*. (2010) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/482/.
137. Outsights-Ipsos MORI. *The Sigma Scan Issue Paper 552*. (2010) [Accessed 2011; Available from: http://www.sigmascan.org/Live/Issue/ViewIssue/552/.

Appendix A : Persistence Scoring Methodology

The information prioritisation process described in Chapter 2.4 is explained in further detail here. This coding scheme provides a framework for prioritising future technologies in a repeatable and consistent way. As each new piece of information is identified, the coding scheme will increment the score for similar technologies already coded within this body of literature.

The scheme calculates the *persistency score* (P-score) of each unique future technology area or concept identified during the literature review. This P-score crudely reflects how mainstream a future technology is likely to be and is therefore an approximation to the likely amount of group-think behind each discussed technology area. It is weighted by the reliability of the sources that referenced it so that information from less reliable sources is valued less than information from reliable sources. A higher P-score will generally indicate more group-think. Lower scores will typify technologies that are not mainstream or that were sourced from less reliable literature sources. The aggregated catalogue of future technologies that appears in Appendix B is ranked according to each entry's P-score. The basis for this method includes the considerations from the information prioritisation criteria described in Chapter 2.4.

Criteria 1 and 2

Criterion 1 requires that information about future technologies obtained from sources employing multi-expert consultations are treated more favourably than those that are sourced from individually authored literature. Criterion 2 requires that any opinion about a future technology be analysed for cultural independence as per the requirements of Chapter 2.3. Sources that are seen to be culturally independent will be treated as more reliable.

Criteria 1 and 2 measure the *reliability,* R[29] of each collected data element on future technologies and ranges from zero to a value of two. The higher the value of R, the more reliable the information about a future technology area is likely to be. Table A-1 shows that a score of zero means that there is both a lack of multi-expert perspectives and that the information from single authors is not culturally independent. Conversely, the most reliable information is found in multiple studies that employ multiple experts in studies that are culturally independent.

---

[29] "R" stands for reliability and is a numerical estimate of how reliable opinion from a literature source is likely to be, based on Criteria 1 and 2.

Table A-1 Range of scores for Reliability

Possible R-scores	**Multi-Expert Views**		**Culturally independent**	
	YES	NO	YES	NO
0		•		•
1	•			•
		•	•	
2	•		•	

Criterion 3
Criterion 3 counts the number of times a particular technology is mentioned within the consulted body of literature. For each occurrence of a reference to the same technology, the score is incremented. The higher the score, the more mainstream a technology is thought to be. Therefore, the effect of the coding scheme outlined here is to balance out the effects of source numbers by weighing the reliability of each data point according to its source. A total measure of persistency is calculated by summing all of the reliability scores for similar technologies already coded within this body of literature, as shown in Equation 1.

For example, for each literature source we first measure its *reliability*, R. We then identify each new piece of information that addresses a technology area that is either new or has already been coded within this body of literature. Every time a new piece of information on future technologies is collected, it is given a reliability rating, R. A *persistency* total is calculated by summing all of the *reliability* (R) scores for similar technologies across this entire body of literature. Table A-2 shows how this method was applied to calculate the persistency of a technology area, titled "*Bio-mechanical robotic integration and biomimetic devices*".

Table A-2 Calculation of a Persistency score for a single future technology area, titled "Bio-mechanical robotic integration and biomimetic devices".

Reference (Culture, Year)	**Multi-expert?**	**Culturally independent sources?**	**Reliability (R) rating**
[10] (US, 2006)	Yes	Yes	2
[60] (US, 2009)	Yes	No ([61])	1
[62] (JPN, 2008)	Yes	Yes	2
[63] (US & ESP,2009)	Yes	No ([61], [60])	1
[43] (UK, 2006)	Yes	Yes	2
[28] (UK, 2009)	Yes	No ([61])	1
[61] (NATO, 2010)	Yes	No ([60], [63], [28])	1
[13] (CH, 2006)	Yes	Yes	2
Total persistency (P) score:			**12**

The logic scheme representing the entire process by which information on future technologies was prioritised is shown in Figure 3.

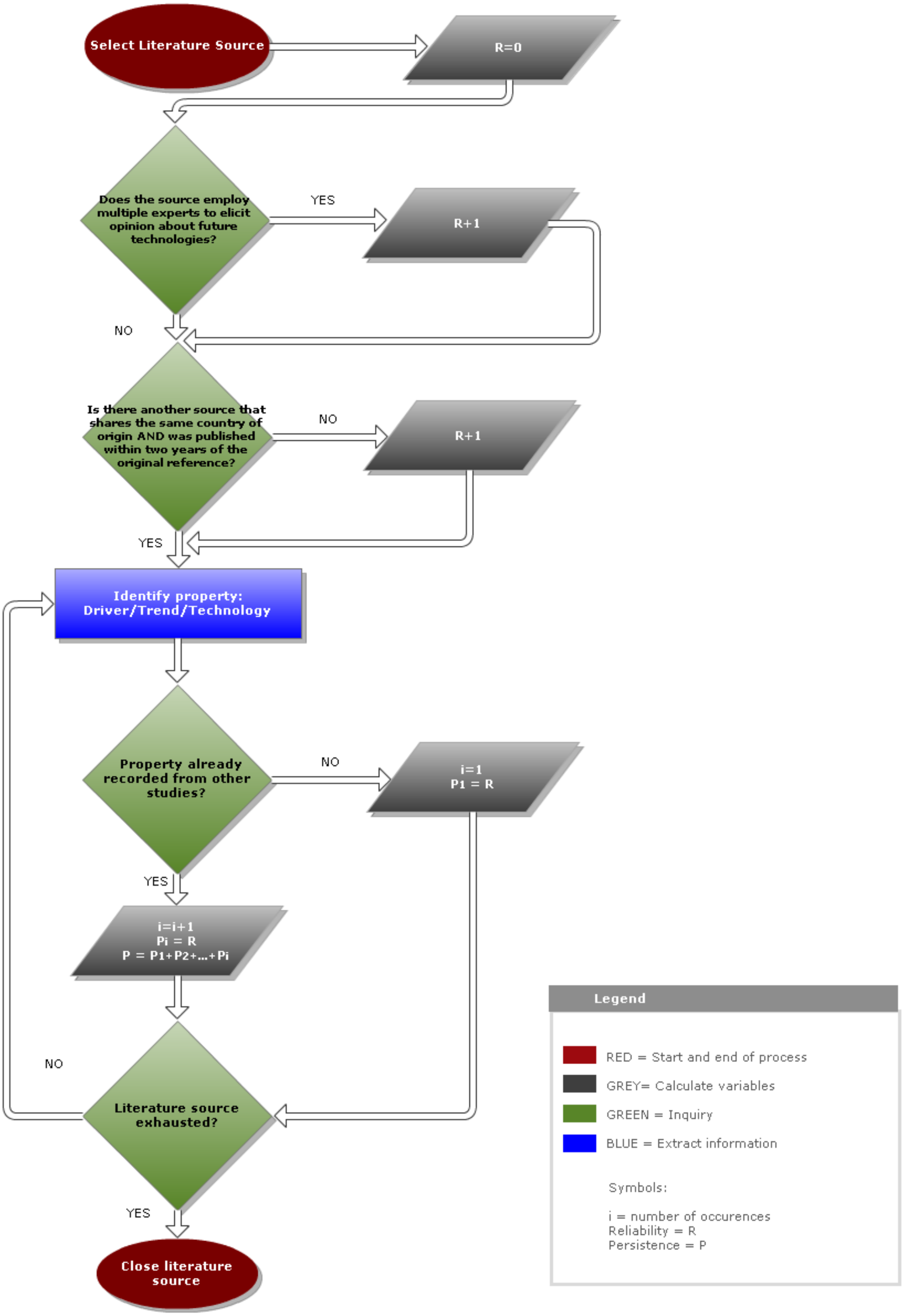

Figure 3. Coding scheme for the literature weighting process (repeated from Figure 1)

Appendix B : Technology Concepts

Literature scanning was used to identify a broad range of technology concepts that were conjectured to emerge in the future. The scan included technologies that were seen as emerging in the near as well as the long-term. This captured technologies that were projected to appear as early as 2020 but whose properties would affect similar technologies in the 2030 timeframes and beyond. It is hoped that by scoping such near-term technologies, generations of dependant concepts that are advanced from near-term technologies could potentially be identified in subsequent SME consultations.

Tabulated lists of technologies, estimated emergence timeframes and their cross-disciplinary applications were developed. Technology concepts were themed according to a key property and grouped within broad taxonomic descriptions.

Seven broad technology application areas were identified:

- Life sciences
- Materials and Manufacturing
- Computing and AI
- Communications and sensing
- Energy
- Vehicles
- Space

These were further broken into more specific technology themes. An individual technology was thus grouped according to its predominant application area and based on its specific application, grouped under a single common descriptor for technologies that are similar.

B.1 Life Sciences

B.1.1 Pharmacy/Medicine/Food

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Drug delivery and targeting including personalised treatments using molecular recognition	Biological augmentation	Designer gene therapy; embryonic treatment of hereditary diseases. Use of nucleotide polymorphism to tailor individual requirements to pharmacological treatments.	2015- 2020+	8	[10]; [61]; [64]; [62]
Computational drug design and testing	Simulation	Modelling and mathematics to develop working models of complex biological processes for the identification of disease and prediction of DNA interactions. Nascent fields such as biosimulation, pharmacogenomics are expected to mature first and will give rise to fully predictive biomedicine for development of tailored treatments, including addiction. “Laptop labs” will allow the simulation of bio-processes in the early design of drugs.	2020-2060	10	[10]; [62]; [13]; [65, 66]
Medical nanostructures for drug delivery	Biological augmentation; Materials	Metal (gold) covered non-conducting nanoshells are injected into cancerous tissue. Nanoshells have been injected with a specific antibody specific to that type of cancer so that the shells bind to cancer only. Once light of specific frequency is shone, nanoshells emit heat and kill the cancer.	now-2020	6	[10]; [62]; [67]
Nanobiology	Materials; Sensing	Application of nanotech to treat disease and detect changes on nano-level (better drug delivery and vaccine development, advanced nano-sensing of CB threats, sensing of biological signatures)	2020	4	[43]; [62]
Genetic modification of biological organisms	Biological Augmentation	Control of pests, disease and improvements in food production. Stem-cell therapies to supplant pharmacological approaches.	2020	6	[10]; [13]; [68]
Water purification using nanotechnologies	Materials	Use of nanoscale porous membranes to improve the efficiency and reduce the size and energy consumption of desalinisation plants. Nano-ceramic sponges can remove industrial contaminants; biofilters can remove bacteria viruses and prions. Nanoscale purification, disinfection and measurement are expected to standardise wastewater treatment that is more efficient, effective and small.	2015-2030	4	[10]; [69]

B.1.2 Analytics and Sensing

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Advanced biometrics	Sensing; AI	DNA pattern recognition. Behavioural and passive biometrics. Facilitated by detection and characterisation of traces of DNA from as little as a single molecule, complex sensory networks and computational models. Ubiquitous sensing and embedded biometric algorithms [10]. Speech and language recognition [61]. Intelligent information processing based on aural language comprehension, biological characteristics [13].	2020-2030	8	[10]; [61]; [13]; [70]
DNA microarrays, rapid bioassays and nanowire sensors	Sensing; Materials	Enable optoelectronic and chemical detection of DNA for testing against viruses, toxins, drug interactions – could replace current microarrays. Correlation of DNA interactions with physical processes.	2020-2030	6	[10]; [13]; [71, 72]
Biological process identification and modelling	Information processing	Use of RNA interference techniques to rapidly link DNA functions to biochemical processes (2012-2019) [73]. Development of mathematical models of complex biological systems (2050) [74].	2020-2050	4	[65, 73, 74]
Environmental models and complex simulations	Information processing	Application of complexity theory [75] to modelling biological systems and environmental processes. Design of efficient operations and urban planning. Accurate climate and weather modelling. Predictive and accurate models of anthropogenic climate effects [76].	2020-2030	4	[62, 75, 76]
Neurochemical behavioural markers and mapping of high-order brain functions	Information processing; Sensing; AI	Development of cognitive sensors for brain-machine interfaces and human mental performance augmentation. Integration of massive analytics to understand neural computations, learning and pattern recognition.	2020	4	[62, 77]
Embedded health monitoring sensors	Pharmaceuticals; Biological Augmentation	Remotely accessible, embedded sensors for individual performance and health monitoring. Instantaneous delivery of treatments in emergency situations to combat pathogens and adverse biological symptoms. Highly selective miniaturised sensors for chemical and biological threats.	2020-2030	4	[10]; [61]
Widespread sensor networks	Sensing; Information processing	Miniaturised, self-powered, processing-enabled sensors that are ubiquitous globally. Enabling massive data gathering and analysis about living organisms and infrastructure. Aided by growth in embedded sensors and computational devices in personal goods.	2020	4	[10, 78]
Accurate prediction and modification of human behaviour and intent	Biological augmentation; AI; Information processing	Modelling of human cognition based on biological processing [43]. Application of statistical methods to behaviour modelling and prediction of behaviour [18]. Reasoning under great uncertainty. Use of applied sociology across multiple scientific disciplines [28]. Combination of neuroscience and psychiatry for brain imaging and high-level functional mapping [28].	2020-2030	8	[43]; [18]; [61]; [79-81]

B.1.3 Biological augmentation and Human-machine interfaces

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Artificial implants for improvements or recovery of biological functions, including brain-machine interfaces	Materials	Controlling/mimicking high-order biological functions through synthetic means [62], [10]. Artificial extensions of human capabilities, including brain repair (2020-2030) [82]. Long lasting, bio-compatible cochlear, optoelectronic implants for better sensing performance [61]. Brain-machine interfaces [18], [43], [10].	2020-2030	8	[62]; [10]; [82]; [61]; [18]; [43]
Pharmaceutical or biological human performance modification	Pharmaceuticals; Materials	Use of drugs for increased cognition, performance, reduced sleep [83]. Pharmaceutical improvements to intelligence, memory, endurance (2030-2060) [84], [18], [43]. Behaviour modification [43]. DNA modification for offspring selection based on performance characteristics (2030-2060)[85]. Understanding and treating brain conditions [62].	2020-2060	7	[13]; [18]; [43]; [62]; [83-85]
Restoration/regeneration of human body parts		Skin, tissue and organ growth on nanopatterned scaffolds [61]. Bio-engineered tissue and organs grown in-vivo [10].	2020	6	[61]; [62]; [10]
Integrated machine control	Information processing; Sensing	Wearable computers for device control. Hands-free interfaces and input devices (voice recognition, gestures, optical sensing) for rapid communication of intent to autonomous systems.	2020-2030	6	[10]; [18]; [62]
Immersive optical interfaces	Sensing; Materials	Contextual, flexible and interactive displays augmenting human visual perceptions to provide a fully seamless simulation or entertainment experience and extending visual capacity.	2015-2030	2	[86, 87]

B.1.4 Biomimetics and synthetic biology

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Bio-mechanical robotic integration and biomimetic devices	Biological Augmentation; Aerodynamic configurations	Introduction of biomimetic implants [10] and biologically inspired mechanical concepts [60]. Remote control of insects in flight [63]. Development of bioelectronic devices [62]. Application of biomimetic robotics [88]. Autonomous decision making on robotic platforms [61]. Intelligence [sic] service robots [13].	2020-2035	12	[10]; [60]; [62]; [63]; [43]; [88]; [61]; [13]
Bio-factories and biological substrates	Materials; Manufacturing Energy	Large scale manufacturing of synthetic biochemicals [89]. New discoveries of reproducible biological processes and molecules [73]. Mass application of artificial photosynthesis to organic solar cells (artificial leaves) [90]. DNA modification of animals and plants to produce new materials (spider silk spinning from goat milk) [29]. Use of silk worms to spin spider silk [91].	2020-2030	9	[89]; [73]; [90]; [10]; [29]; [91]
Synthetic biological engineering	Materials	Manufacture and application of synthetic chemicals such as bioactive peptides to target specific cellular receptors and affect human behaviour. Developments in genomics and proteomics to create synthetic organisms engineered to achieve specific tasks.	2020+	2	[43]

B.2 Materials and Manufacturing

B.2.1 Materials

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Nanomaterials and structures	All	Application of nanotechnology to embed multifunctional characteristics into materials.	2018-2030	12	[43];[92];[62]; [93-95]; [18]; [96]; [13]
Metal-organic compounds	Space; Energy; Transport	Structural self-assembly. Safe hydrogen storage. CO2 capture. Mass manufacture of organic electronics.	2012-2020	4	[97, 98]
Biomedical materials	Biological augmentation; Biomimetics & Synthetic Biology	In-situ cellular and organ self-repair. Tissue engineering and regenerative medical applications.	2030-2060	4	[92, 99]
Specialised, high-performance coatings	Vehicles; Space	Multi-functional coatings that improve existing material strength, endurance, reduce friction, lower RF signatures and increase resistance to environmental hazards.	2020	2	[92]
De-icing composites	Vehicles; Space	Composite materials that actively remove ice crystals or impede their growth.	2030	2	[92]
Electronic materials	Computing and AI; Communications and Sensing; Vehicles	Specifically programmed materials with embedded functional elements. Combined photonic and electronic effects. Large band gap semiconductors that operate at high frequencies [61].	2020	7	[10]; [61]; [92]; [43]; [18]; [100]
Smart fabrics	Vehicles; Human-machine Interfaces	Fabrics embedded with electronics, power sources and optoelectronics [10]. Protective clothing, bioactive textiles that remove toxins, electronic textiles capable of remote sensing, adaptive textiles incorporating actuators, reactive textile that respond and change shape to external stimuli such as impacts [92]	2020-2030+	6	[10]; [92]; [43]
Self-healing materials	Vehicles	Routine self-repair and maintenance performed automatically and in flight [60].	2030	3	[92]; [18]; [60]
Room temperature ferromagnets and superconductors	Computing and AI; Communications and Sensing	Use of new materials for high density data storage, new computing architectures such as mermistors and quantum computing and high-energy applications.	2030	7	[62]; [18]; [101]; [92]; [13]

Carbon nanotube	Food; Vehicles; Space; Sensing; Energy	Portable and inexpensive water purification using CNT membranes and filters. Use of CNTs to create new composites that are stronger and lighter – CNRPs. These may be used to create efficient morphing wings, radiation resistive space hardware, impact resistance; space elevator. More immediate applications will be to lighten vehicles where performance is secondary to cost. Integrated sensor ability using nanotubes. Nanotubes can be used to store energy in capacitor-like structures as well as storing hydrogen at non-cryogenic temperatures [29]. Applications to low energy computing.	2020	7	[18]; [102]; [10]; [29]
Nanowires	Computing and AI; Communications and Sensing; Energy; Space	Extremely low resistivity and vast increases in electronics' efficiency. Used in the replacement of copper wires and as heat sinks as they have great thermal conductivity. Can be used in miniaturising spacecraft. May exhibit superconductivity near room temperature. Improvements in greater battery energy densities compared with Li-ion devices	2020	2	[103]
Quantum materials	Computing and AI; Communications and Sensing; Energy	Materials with tailored quantum effects for use in quantum computers, high-temperature superconductivity or lasers. Macro-quantum effects of photonic material, new principles for quantum manipulation characterising and measuring.	2030-2060	4	[13, 104]
Reactive materials and structures	Vehicles; Human-machine Interfaces	Shape-adaptive materials that react to electric currents, kinetic forces. Shape-memory materials that can be programmed to take on certain configurations in specific environmental conditions. Reactive nano-armour composites for battlefield use. Impact resistant rheo-fluidic systems [92].	2012-2030+	4	[84-86, 97]
Next generation low observable materials	Vehicles; Sensing	Adaptive camouflage in the visible and microwave regions [61]. RF absorbing metamaterials with reduced EO/IR visibility.	2020-2030+	7	[61] ; [92]; [43] ; [18]; [60]; [13]
Silicon photonics	Information processing; Communications and Sensing; Directed energy	Optical processing on future computing platforms for massive decreases in heat dissipation and increases in processing speed.	2017+	4	[105], [106]

B.2.2 Manufacturing

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
DNA fabrication techniques and nanomolecular manufacturing	Pharmaceuticals; Biological augmentation	Application of molecular self-assembly and programming using DNA information on a macroscopic scale.	2020-2030	6	[10, 107]; [13]
On-demand manufacturing	Energy; Materials; Human-machine interfaces	Development of 3D printers with multifunctional materials to produce complex designs for the end user. Low complexity, low-energy manufacturing. Decreased reliance on mass production and factories.	2020	6	[108, 109]; [10]
Programmable manufacturing	Biological augmentation; New computing architectures; Materials	Nano-brick self-assembly into functional electronic, mechanical, optical or biological structures. Creation of quantum nanostructures for use in brain repair or quantum computing. Manufacturing technology using advanced information technology and service robotics.	2020-2030	6	[62, 107]; [13]
Quantum chemistry	Information processing; New computing architectures	High fidelity chemistry models used in the prediction of reaction rates, energy flows and chemical pathways to maximise reaction efficiencies and reduce waste by products.	2030-2060	2	[110]
Green chemistry and manufacturing	Energy; Materials	Use of biomass and low toxicity chemicals in manufacturing. Development of new chemical reactions and process simulations to support efficient manufacturing.	2020-2030	6	[1, 4, 103]
Extreme manufacturing	Materials	MEMS, NEMS for precision manufacturing; extremely powerful functions for operations in extreme environments.	2020	4	[13]; [111]

B.3 Computing and Artificial Intelligence (AI)

B.3.1 Information processing and computing architectures

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Massive analytics	AI; Sensing; Biological Augmentation	Vast databases that may include personal, genetic and biometric information will require supercomputer-like processing power on demand to complete smart contextual searches. Algorithms and computational models could be developed to complete sophisticated pattern matches, track logistics and engage in market trading. Autonomous systems may be supported by similar massive analytics to make real-time decisions under great uncertainty.	2020; 2030	7	[10, 18]; [112]; [113-115]
Semantic web	AI; Communications and Sensing; Simulation	Machine readable context will allow accurate human-machine coupling and data sharing in time-sensitive applications.	2020-2040	4	[17]; [43, 116]
Miniaturised high-density data storage	AI; Communications and Sensing; Vehicles; Space	MRAM and spintronic applications to new computing architectures providing high data densities in miniaturised packages. Possible transistor replacements for miniaturised and more powerful computing architectures. Applications to neuromorphic computer systems and pattern recognition.	2020- 2040	7	[10, 117]; [17]; [44]
Computational sociology and prediction of mass behaviour	Simulation; Bio analytics and sensing; Vehicles	Application of social network modelling and novel cognitive models to estimate human behaviour and intent autonomously.	2012-2030	5	[118]; [18]; [43]; [119]
Bioinformatics	Simulation; AI; Sensing	Data gathering and process identification in complex biological environments using a combination of nanosensors, massive analytics and autonomous reasoning.	2020-2060	8	[66, 74]; [62]; [45]
Accurate weather forecasting	Directed energy; Communications and sensing; Vehicles	Interdisciplinary interaction between complex atmospheric models, sensor networks and new computing architectures with massive processing power will enable accurate decision-level predictions.	2020-2030	4	[62]; [113]
Quantum computing	Materials; Simulation; AI; Secure communications; Space	Will enable massively parallel computations for quantum cryptography, pattern recognition, autonomy and simulations. Quantum informatics, correlated electronics, quantum communication, confined small-scale quantum system and artificial photonic crystal for future IT development [13].	2020-2060	7	[43]; [18]; [120, 121]; [13]

DNA computing	Biological Analytics and Sensing; Materials; AI; Communications and sensing; Autonomous vehicles	Biochemical nanocomputers based on biochemical interactions of protein chains. Will provide very large improvements in computational power and will be self sustaining and have the potential for self-repair. Could be integrated with biological organisms for direct interactions with cellular chemistry and autonomous biological regulation.	2030-2060	2	[122]
Ad-hoc networks	Secure communications	High-flexibility, attack free [sic] data networks and ad hoc intelligent system [13]. Network polymorphism [18].	2020-2030	4	[18], [13]

B.3.2 AI

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Artificial Intelligence and autonomous, intelligent processing	Autonomous vehicles; Communications and sensing	Gearing human intensive functions through processing-enabled devices. Robotic decision making based around autonomous reasoning and learning. Use of distributed sensing to be aware of environments. Trusted autonomy that can be validated.	2030-2040	5	[18]; [61]; [86]; [60]
Software agents	Autonomous vehicles; Communications and sensing	Self organising and evolving software. Intelligent agents and bots. Automated software generation based on signal data recognition and autonomous learning within complex environments.	2020-2030	4	[18]; [61]; [86]
Cyberspace UAV	Information processing; AI; Secure communications	Software agent that is adaptive and flexible while under cyber threats. Monitors and conducts ISR on the cyber environment. Repairs friendly nodes affected by malicious cyber operations	2025	2	[47]

B.3.3 Simulation and training

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Immersive collaboration tools	AI; Communication; Autonomous vehicles	Self-organising networks for information management and flow. Community computing grids for efficient resource allocation and parallel computing. Peer production networks for rapid problem solving. Social mobile computing that supports collaboration and problem-solving in ad-hoc situations.	now-2020	2	[123]
Virtual synthetic environments and adaptive training	Information processing; Human-machine interfaces	Cultural, social and combat training [61]. Virtual surgery [124]. Quantitative simulations of social interactions [6]. Data mining of social interactions such as online social networks or MMOG to quantify relationships and establish predictive models [18]. Continuous, adaptive training [43].	2015-2030	6	[61]; [124]; [43]; [18]; [13]

B.4 Communications and Sensing

B.4.1 Sensing and Navigation

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Pervasive, undetectable sensor networks	Information processing;	Real-time data mining and health monitoring using NEMS or MEMS based sensors. Embedded combat ID. Smart-dust sensors that are completely undetectable and persistent [29].	2020	5	[10]; [61]; [29]
Hyperspectral and terahertz sensors	Materials; Information processing	Stand-off detection of substances such as explosives and chemical agents. Improved imaging systems for vision through surfaces such as water, walls and vehicles. Multispectral sensor swarms [29].	2020-2030	3	[61]; [29]
On-chip BWA identification	Materials; Life-sciences	Immediate recognition of toxic biological agents using nanosensors or DNA sensing techniques.	2020-2030	2	[61]
Stand-off laser detection of explosives	Materials, Information processing	Ranged detection using a plasma pulse to evaporate small amounts of substance. Line of sight effects only.	2015-2020	2	[61]
Miniaturised radar for UAV and personal applications	Materials	Use of NEMS/MEMS and high density energy storage to create a light-weight, portable radar system.	2020-2030	2	[92]; [60]
Autonomous and self organising sensor	AI; Information	Processing enabled sensors that autonomously track their environment and	2030-2035+	4	[18]; [43];

networks	processing; Autonomous vehicles	can optimise placement for maximum data collection and interpretation.			[60]
Highly portable or wearable inertial and position, motion and acceleration devices	Materials; Directed Energy	Chip-scale (micro and nano) atomic clocks for accurate timing in GPS-denied environments. Cold atom interferometric devices for acceleration measurements Highly portable or wearable inertial and position, motion and acceleration devices	2030	4	[18]; [60]; [43]
Hyperprecision munitions	AI; Information processing; Autonomous vehicles; Materials	Use of autonomous munitions and networked sensors to provide real-time accurate ISR.	2030	2	[18]
3D maritime environmental monitoring	Information processing	Synchronised monitoring from space, offshore stations, water surface, and in-water. Research will be focused on remote marine sensing technology, acoustic probe technology, buoy technology, shore-based long-range radar technology, and marine information processing and application technology [13].	2020	2	[13]
Deep sea sensing	Materials, Information processing	Ocean floor-based multi-parameter fast sounding technology, gas hydrates mining, deep-sea sample collection and communications.	2020	2	[13]

B.4.2 Secure Communications

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Secure wireless links	Information processing; AI; New computing architectures	Development of highly secure wireless, RF data links [61] and encryption protocols for cloud computing applications [125-127] and ubiquitous equipment-sensor links [61]. Protocols will utilise polymorphic networks and may be highly frequency-agile and adaptive in order to be as resilient to cyber attacks as possible. Automated vulnerability assessments and reactions will allow such systems to maintain operational efficiency under ongoing cyber threats [18].	2020	6	[125-127]; [61]; [18]
Laser communications	Directed energy; Materials; Information processing	Application of quantum key distribution to encrypt high bandwidth laser communications and provide full-spectrum access to communication channels in congested environments.	2030	4	[18]; [128]
Persistent near-space communication relays	Materials; Energy; AI	HALE airships with advanced thermal and meta-materials. Self monitoring and autonomy will further ensure survivability [18].	2030	2	[18]

B.5 Energy

B.5.1 Directed Energy

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Short-range laser defence	Materials; AI; Information processing	Destruction of air threats using MW-class, precision laser weapon. It can sense and track multiple targets and instantaneously engage it.	2015-2030	4	[61], [13]
Femtolaser	Materials; Fuel/power sources	Self focusing, high power laser	2025 TRL2	2	[61]
Space-based lasers	Materials; Space; Fuel/Power sources	Two concepts: ground based laser with mirrored space relays or a space-based solid-state laser.	2030	2	[47]
Future airborne laser	Materials; Fuel/power sources	Aircraft mounted nuclear-powered laser on board a manned platform with extremely long endurance (crew-limited).	2030+	2	[47]
Tactical airborne laser	Materials; Fuel/power sources; AI; Autonomous vehicles	Use of solid-state and fibre laser systems [18] to provide 300kW power [47] and autonomous self defence against missile or aircraft threats. Possible tactical strike use.	2030+	2	[47]; [18]
Microwave and RF DEW	Materials	Delivery of electronic attack using directed energy to disrupt electronic components and personnel. Microwave beams will cause painful sensations with no lasting damage. RF attacks will damage electronics.	up to 2040	2	[17]

B.5.2 Energy Generation and Storage

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
High-density/high-efficiency energy storage technology	Materials	Hydrogen fuel cell development [62] and use of CNT structures to ensure safe hydrogen capture and storage. Synthetic development of specialised high energy materials [10],[62]. Large scale applications of super-capacitors. Efficient rechargeable cell materials and supercapacitors [13].	2020	6	[10]; [62]; [13]

Controlled fusion power	Materials; Simulation; Directed energy	New confinement, simulation and material could produce an operational reactor by 2030 and commercialisation no earlier than 2040. Research into large superconducting magnets, microwave heating, beam injection heating, materials, high-temperature plasma physics and non-Tokamak approaches to fusion [129].	2030-2060	4	[17]; [129]
Biofuels and synfuels		Production of fuels from biomass generated in shallow sea/desert conditions. Produces petrochemical feedstock in a closed CO2 cycle (carbon neutral) [29]. Replacement of petrochemical sources with synthetic alternatives that are mass produced and not oil-dependant. Use of tactical biorefineries to convert waste and garbage into energy [130].	2025+	6	[29]; [131, 132]; [13]
Microreactors	Materials; Biomimetics and Synthetic biology	Nanoengineered molecular reactors harnessing biochemical reactions inside living organisms or as part of a synthetic bio-machine. Very efficient, invisible and portable.	2020+	4	[43]; [62]
Next-generation nuclear reactors	Materials	Fourth generation nuclear energy systems with increased efficiency. Fast neutron reactor technology (breeder) [13].	2020	2	[13]

B.6 Vehicles

B.6.1 Propulsion

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Hypersonic air-breathing engines	Materials; Autonomous vehicles; Sensing	Propulsion technology and materials that can withstand the extreme temperatures of hypersonic flight will take another 20 years to develop [60]. Automatic diagnostic and prognostic systems will allow reusable combined rocket/scramjet platforms for low cost orbital insertion [18]. Inward turning inlets and dual flow paths will provide high volumetric efficiencies [18]. Hypersonic transatmospheric aircraft to deal with heat issue as above Mach 10 [61].	2030	5	[61]; [18]; [60]; [52]
Next generation high-efficiency turbine engines	Materials; Sensing; Energy generation and storage	Alternate fuels, serpentine nozzles, health monitoring, MEMS flow control and nanomaterials will be used to deliver efficient embedded turbine engines for future aircraft configurations [18].	2030	4	[18]; [133]
Dual mode propulsion (supersonic/hypersonic)	Sensing and navigation; AI	Dual mode propulsion (supersonic/hypersonic) stand-off missile with optical terrain following, advanced EW and jam-resistant PNT systems.	2030	2	[18]

B.6.2 Configurations

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Supersonic/hypersonic bomber	Materials; Information processing; Sensing and navigation	Operational readiness of a new bomber platform is not likely until 2037 or beyond [134]. Low observables in a supersonic configuration are the likely future requirements.	2037+	3	[47]; [57]; [134]
Hypersonic aircraft	Materials; Energy generation and storage; Propulsion; Space	Trans-atmospheric vehicle with global radius. Allows rapid, reusable access to space and orbital payload insertion. May have combined-cycle propulsion (rocket/scramjet) with vertical takeoff	2025, 2032	2	[47], [18]; [96]
HALE airships	Materials; Autonomous vehicles; Space; Energy generation and storage	Long endurance, large lift capacity, faster than equivalent seafaring transport options, large sensors. Requires high-altitude, radiation hardened materials. Lightweight solar panels and high density energy storage technologies. Multi-functional sensor structures. Has onboard health monitoring and potential self healing capabilities. Microwave power beaming for propulsion [54].	2030	2	[54];[18]

Hybrid wing-body aircraft		Highly unstable dynamically and requires fully automatic actuation and autonomous control under a variety of environmental conditions.	2030	2	[18]
MEMS flow control	Sensing; AI; Materials	Micro flow control to eliminate control surfaces and reduce drag by 80% [133]. Application to lifting surfaces and propulsion systems. Observability reduced.	NA	2	[133]; [135]
Autonomous swarming vehicles	Sensing; AI; Autonomous vehicles	Miniaturised, autonomous agents with a shared sensory network capable of swarming and re-organising in response to external conditions or operator intent.	2030-2040	4	[18]; [60]; [17]

B.6.3 Unmanned and Autonomous Systems

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Fractionated, survivable, remotely piloted system	AI; Information processing; Sensing; Space configurations	Modular, composable platform that has autonomy in takeoff and landing. Has basic swarming elements for collaborative organisation. Low observable and expendable.	2030	2	[18]
Wingman UAS	AI; Sensing; Secure communications	UAS accompanies a manned aircraft to conduct ISR, air interdiction, IADS attacks, offensive counter air, C2 of micro-UAS and provides additional weapons payload to the main aircraft. The wingman UAS can also be a transport or refuelling platform [60]. Has embedded electronic EW (jamming) capability, self repair and diagnosis systems [47].	2020; 2025	2	[60]; [47]
Automated highways and vehicles for increased capacity and safety	AI; Sensing; Information processing	Congestion and safety improvements in dense urban infrastructure. Management and autonomous, intelligent coordination of traffic flows both within and without the vehicle. Requires a persistent sensor network for complete traffic monitoring.	2015-2020	2	[136]
Unmanned space exploration	AI; Space; Energy generation and storage; Materials	Unmanned space exploration will continue to far outnumber human space exploration with autonomous and sensor systems advanced as a result.	ongoing	2	[137]

B.7 Space

B.7.1 Guidance and Control

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Persistent SSA	Materials; Information processing; Communications and sensing	Allows birth to death detection, tracking, advanced collision warning. Requires massive data fusion across sensor platforms. Use of a Space Based Surveillance system for detection and tracking including identification of payload using EO/IR sensors.	2030	2	[18]
Orbital Conjuction Prediction	Simulation; Communications and sensing	Predictions of environmental interactions on spacecraft and their orbits. Monitors space weather, sensors fusion (SSA), satellite drag models. Will provide enough confidence in predictions to manoeuvre space assets out of harms way, if needed.	2030	2	[18]

B.7.2 Configurations

Technology	Cross-disciplinary effects	Application examples	Horizon	P-Score	Sources
Hypervelocity rod bundles for kinetic bombardment	Orbital prediction and tracking; Materials	Tungsten rods delivered de-orbited from an orbital satellite platform striking global targets at orbital speeds.	2015+	2	[57]
Reusable Air breathing Access-to-Space Launch	Propulsion; Materials; Communications and sensing	Vertical takeoff space launch using rocket first stage and air breathing rocket-scramjet second stage. Requires advanced thermal materials, automation, onboard health monitoring systems.	2030	2	[18];
Rapidly Composable Small Satellites	Materials; AI; Communications and sensing	Modular components for fast insertion. Includes automatic recomposition should systems fail, communications via secure links. Cooperative control, guidance, on-orbit self-assembly. Attitude control, orbital manoeuvre, communications, ISR, weapons modules.	2030	2	[18]
Fractionated/Distributed Space Systems	Materials; AI; Communications and sensing	Provides redundancy, survivability and system upgradeability. Fractionation will involve system elements that cooperate and communicate via secure, jam-resistant links (laser). Such systems are easily added to/repaired by adding or substituting small satellites.	2030	2	[18]

Page classification: UNCLASSIFIED

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION **DOCUMENT CONTROL DATA**	1. PRIVACY MARKING/CAVEAT (OF DOCUMENT)

2. TITLE Future Technology Themes: 2030 to 2060	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)
4. AUTHOR(S) Nik Luketic	5. CORPORATE AUTHOR DSTO Defence Science and Technology Organisation 506 Lorimer St Fishermans Bend Victoria 3207 Australia

6a. DSTO NUMBER DSTO-TR-2877	6b. AR NUMBER AR-015-680	6c. TYPE OF REPORT Technical Report	7. DOCUMENT DATE July 2013

8. FILE NUMBER 2013/1088098/1	9. TASK NUMBER AIR 07/036	10. TASK SPONSOR DGSP-AF AIRCDR Andrew Dowse	11. NO. OF PAGES 70	12. NO. OF REFERENCES 137

13. DSTO Publications Repository http://dspace.dsto.defence.gov.au/dspace/	14. RELEASE AUTHORITY Chief, Joint and Operations Analysis Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111

16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CITATION IN OTHER DOCUMENTS Yes

18. DSTO RESEARCH LIBRARY THESAURUS http://web-vic.dsto.defence.gov.au/workareas/library/resources/dsto_thesaurus.shtml

Literature surveys, Futures analysis, Qualitative analysis, Technology forecasting, Qualitative data analysis

19. ABSTRACT

In support of Air 07/036, DSTO seeks to explore new areas of technology that might be available over the next 20 to 50 years. There is a vast body of literature on the direction the developments in future technologies may take. Described here is a literature coding method that was developed for the purposes of this study. The method selects only sources that originate from expert views and applies a weighting scheme that aims to ensure the inclusion of independent and unique perspectives. The result is a diverse, ranked list of 100 future technologies appearing out to 2060 based on an analysis of the open literature. The report also includes a brief discussion of future environmental issues that form the context to the hypothesised technological developments. This technique developed here is suitable for conducting traceable and thorough literature reviews with limited analytical resources.

Page classification: UNCLASSIFIED