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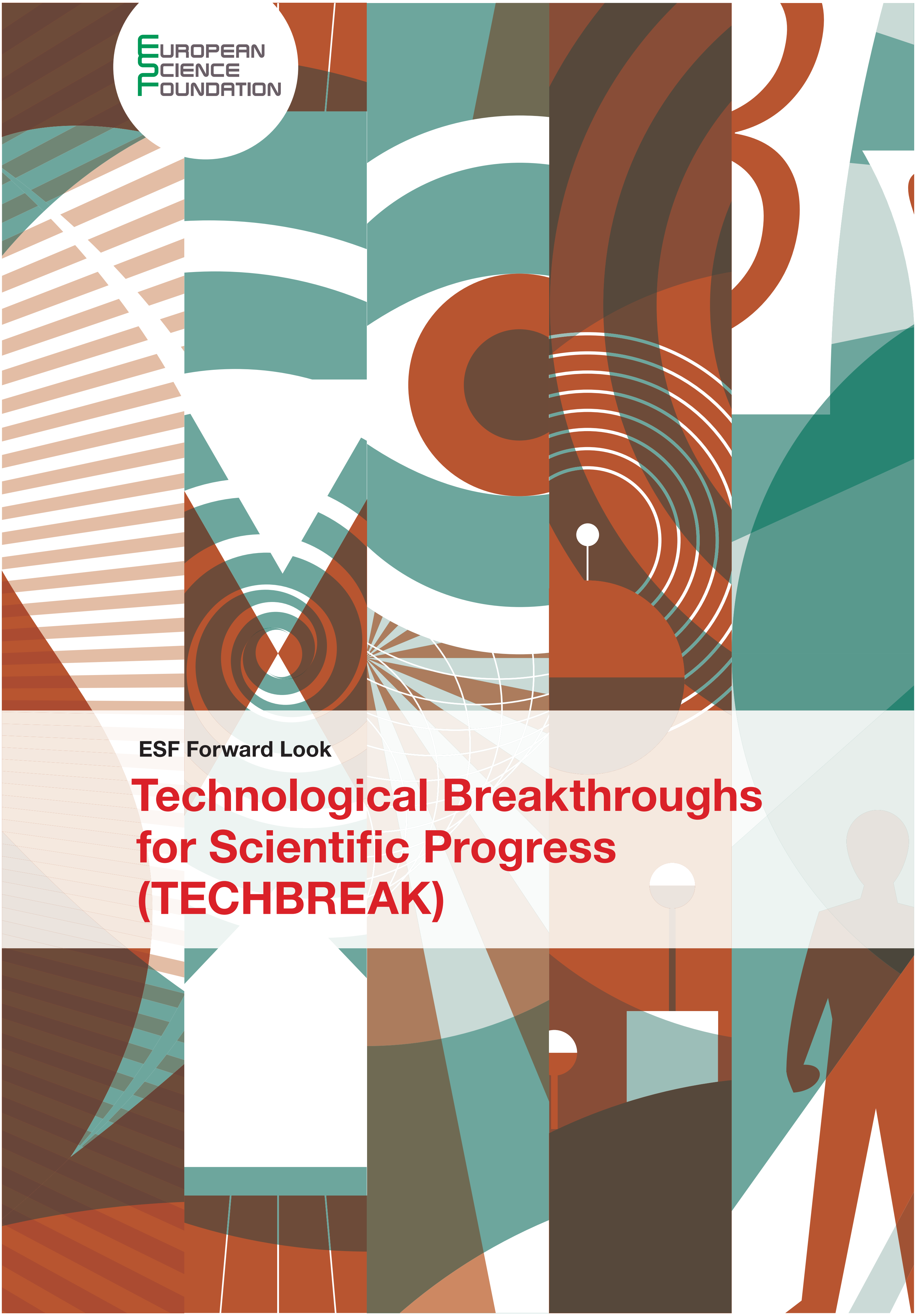

ESF Forward Look

Technological Breakthroughs for Scientific Progress (TECHBREAK)

European Science Foundation (ESF)

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Foreword

The European Science Foundation (ESF) was contacted at the end of 2009 to conduct a foresight activity for ESA, addressing the delicate matter of technological breakthroughs for space originating in the non-space sector. A joint ESF-ESA "Forward Look" project called 'TECHBREAK' was initiated as a result. Its goals were to forecast the development of such breakthrough technologies to enable novel space missions in the 2030-2050 timeframe, and to identify related partnerships through synergies with non-space specialists.

This report to ESA's Director General and High-level Science Policy Advisory Committee (HISPAC) is the result of this exercise. It was not prepared to serve as a definitive guide for very specific technologies to be developed for future space missions, but to inform on and flag up the main developments in various technological and scientific areas outside space that may hold promise for use in the space domain. The report does this by identifying the current status of research for each domain, asserting the development horizon for each technology and providing some entry points, in the form of key European experts and institutions with knowledge of the domain. The European Union's concept of Key Enabling Technologies (KETs) was chosen as a guide through this technological search.

The identification of problems and solutions specific to the space area led to focus the discussion around the concept of "Overwhelming Drivers" for space research and exploration, i.e. long-term goals that can be transposed into technological development goals. This is the main focus of TECHBREAK. We firmly hope that these Overwhelming Drivers will be used throughout ESA's Directorates as a novel categorisation of programme concepts and useful red thread to guide the reflexion about future missions and related technological maturation.

Dr Martin Cullum
Chair, TECHBREAK Scientific Committee

Professor Jean-Pierre Swings
Chair, European Space Sciences Committee

Mr Martin Hynes
ESF Chief Executive

Executive Summary

In space sciences, as well as in 'mainstream' science, the development of innovative technologies opens new fields of research and provides sophisticated new tools for scientists. However, the experience of the past decades of space research has demonstrated that a conservative approach to technology is too often followed: self-censorship is often applied regarding space technologies that are not yet fully proven, for fear of losing in competitive assessment phases. The result is that evolution is gradual and breakthroughs do not happen as frequently as they could.

The European Space Agency's end-to-end process for technology development is user driven, which means that work plans for technology development are mostly identified from the needs of the candidate space missions that are selected under established transparent mechanisms, where feasibility and level of maturity are key criteria for selection. When missions are selected, failure to make technology available in a timely manner results in cost and schedule overruns which result, in the frame of given budgets, in new missions being delayed. The risk analysis and avoidance procedure that is built into the project selection process, coupled with the risks associated with new technologies, thus automatically leads to penalising proposals that are based on new and untried technologies. As a result, ESA may have to deal with obsolete technologies in a fast developing field, thereby losing competitiveness and leadership.

A way of removing blocking factors and enabling scientific breakthroughs in space could be spinning-in advanced technologies that are developed in the 'non-space' sector, which is the reason why the search for sources of technology in this foresight exercise was focused outside the traditional space technologies, with the aim of developing interactions and partnerships between space and non-space communities.

The European Science Foundation was contacted in 2009 to conduct this foresight activity, and a joint ESF-ESA Forward Look project called 'TECHBREAK' was initiated as a result. The ESF has been collaborating with European scientists across all disciplines for the last 40 years and is an integral part of the European scientific landscape. Furthermore, the European Space Sciences Committee (ESSC), which operates under the umbrella of the ESF, is very well connected with the European space sector. The TECHBREAK project, equally funded by ESA and ESF, was created to leverage these connections, with the objectives of:

1. Taking stock of breakthrough scientific objectives;
2. Identifying partnership schemes through synergies with non-space specialists;
3. Forecasting the development of technologies for the achievement of scientific breakthroughs to enable novel space missions in the 2030-2050 timeframe;
4. Foreseeing the evolution of the technologies in space and non-space domains;
5. Preparing a final Forward Look report to be submitted to ESA's Director General and High-level Science Advisory Committee.

The goal of this report is not to serve as a definitive guide on which exact technologies should be developed for future space missions. Rather, it was prepared to inform on and flag up the main developments in various technological and scientific areas outside 'space' that might hold promise for use in the space domain. The report does this by identifying the current status of research for each domain, asserting the development horizon for each technology and providing some entry points, in the form of key European experts and institutions with knowledge of the domain.

The project started concretely in early 2010 with a definition phase during which the Scientific Committee elaborated a foresight strategy and methodology and set up a series of consultations with experts. As a result of these consultations, some of the objectives that were mentioned in the previous section were re-assessed and it was decided jointly with ESA to concentrate on the identification of relevant non-space technologies for infusion into the space sector that had not been known nor used so far in the space context, and might hold promise for this sector. An important point therefore was to identify the right level of granularity at which the availability of such technologies could be assessed for potential spin-in. The concept of Key Enabling Technologies was chosen as a result, in particular to maximise commonalities with the European Union (EU) and synergies.

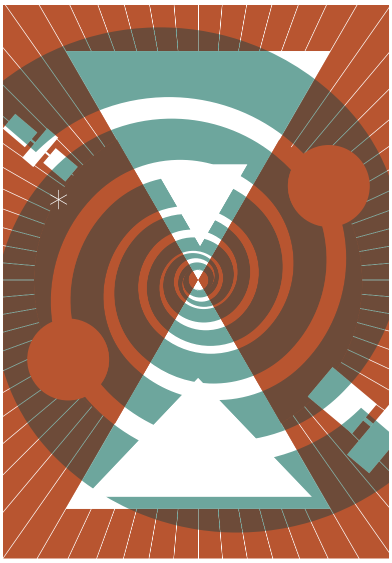
In addition to the meetings of the Scientific Committee supervising the project, a total number of six events and workshops were organised during the course of the project. An early conclusion of the related discussions was that this foresight activity should focus on defining the needs and challenges of the space sector in relation to the potential offered by non-space critical technologies in these domains. The needs and challenges should then be defined and mapped against technological sub-areas in terms of their space relevance. These space needs and challenges were further refined at the various workshops and transformed into specific areas of potential interest for future space missions, i.e., large structures, miniaturisation, propulsion, systems longevity and self-repair capacity, energy supply, sample collection and handling, search for life, new environments and bioengineering, communication, and cryogenics. These were refined throughout the process and fuelled the identification of the technological sub-fields to be considered.

Finally, and most importantly, the discussion concerning the identification of problems and solutions specific to the space area led to focus the discussion around the concept of 'Overwhelming Drivers' for space research and exploration, i.e., long term goals that can be transposed into technological development goals. These drivers represent the main areas where technological improvements are needed in order to be able to generate breakthroughs in space capabilities. The drivers also served as a brief introduction to the space environment and space operations for non-space experts and acted as a stimulant for the identification of potential helpful technologies, therefore bridging the knowledge gap between space and non-space experts. Their definition and utilisation aimed at providing the 'food for thought' stimulus that might result in a spin-in idea, from a KET field into the space domain. Beyond this goal, it is believed that these five Overwhelming Drivers could also be used throughout ESA's Directorates as a novel categorisation of programme concepts and useful red thread to guide reflexion about future missions and related technological maturation.

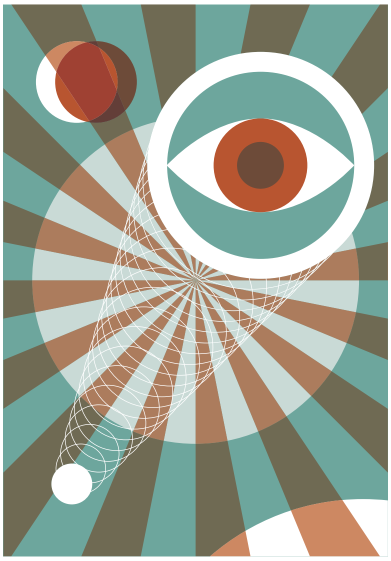
The following drivers were identified:

1. Reduce mass, maintain stiffness

2. Build a spacecraft and space missions that can last 50 years



3. Deploy a 30m+ telescope into space



4. Autonomous geophysical survey of planets

5. Enable humans to stay in space for more than two years

These five drivers are described in detail in the report, along with a codification of the potential solutions from available non-space technologies that are analysed in the various sections of the report.

The assessment of the various technologies that have been encountered in TECHBREAK follows a simplified version of the well known Technology Readiness Level (TRL) used in the space context. The system has been adapted from the description of the TRLs, excluding the space qualification part, since the technologies are for terrestrial systems. The system contains four levels that indicate the technology readiness level. These technologies were also described, when possible, in terms of the expected time to the next breakthrough as well as the size of the community. These assessments are based primarily on the perception of the experts from the TECHBREAK interviews and/or research literature assessment and framework funding information where available.

Finally, contact points for these technologies are provided for potential use by ESA.

1. Introduction

In space science, as well as in 'mainstream' science, the development of innovative technologies opens new fields of research and provides sophisticated new tools for scientists. However, the experience of the past decades of space research has demonstrated that a conservative approach to technology is too often followed: self-censorship is often applied regarding space technologies that are not yet fully proven, for fear of losing in competitive assessment phases. This may be partly due to the very long development times in that domain, but the result is that evolution is gradual and breakthroughs do not happen as frequently as they could.

The European Space Agency's end-to-end process for technology development is user driven. Work plans for technology development are mostly identified from the needs of the candidate missions. Although some significant effort is devoted to breakthrough innovation, most of this effort goes into enabling those specific candidate missions. ESA space missions are selected under established transparent mechanisms, where feasibility and level of maturity are key criteria for selection. Therefore, in proposing missions, scientific teams tend to rely on gradual technological innovation. When missions are selected, failure to make technology available in a timely manner results in cost and schedule overruns which result, in the frame of given budgets, in new missions being delayed.

The risk analysis and avoidance procedure that is built in in the project selection process, coupled with the risks associated with new technologies, automatically leads to the penalisation of proposals that are based on new and untried technologies. Furthermore, Member States do not invest enough in the development of advanced instrumentation for not-yet-approved missions. As a result, ESA may have to deal with obsolete technologies in a fast developing field, thereby losing competitiveness and leadership. Nevertheless, Europe looks to ESA for innovation in space, with the expectation of acceleration of the pace of scientific discovery through the utilisation of advanced technologies.

A way of removing blocking factors and enabling scientific breakthroughs in space could be spinning-in advanced technologies, even if not developed for space. Therefore the search for sources of technology in this foresight exercise was focused outside the traditional space technologies. The infusion of the best technology to achieve scientific breakthroughs requires interaction between space and non-space communities and the establishment of partnerships. It is thus necessary to look for the desired breakthroughs in science and technology (forward looking), as well as to the concurrent development in enabling technological fields (parallel looking).

The European Science Foundation was contacted to conduct a foresight activity dealing with such technology breakthroughs. ESF therefore launched with ESA in December 2009 a Forward Look project [1] to reply to this request, called 'TECHBREAK'. The topics to be covered in the TECHBREAK report go beyond space-related technologies and address various fields of physics and engineering, since in many domains technology is evolving faster than in the space domain.

The ESF has been collaborating with European scientists across all disciplines for the last 40 years and is an integral part of the European scientific landscape. Furthermore, the European Space Sciences Committee, which operates under the

1. http://www.esf.org/activities/forward-looks.html

umbrella of the ESF, is very well connected with the European space sector. The TECHBREAK project was thus created to leverage these connections. The project was equally funded by ESA and ESF (after approval by its governing council).

1.1 Objectives

The general objectives of the TECHBREAK foresight activity, as stated in the initial Statement of Work, were to:

- Take stock of breakthrough scientific objectives;
- Identify partnership schemes through synergies with non-space specialists;
- Forecast the development of technologies for the achievement of scientific breakthroughs. These technologies should enable novel space missions in the 2030-2050 timeframe;
- Foresee the evolution of the technologies, in space and non-space domains;
- Prepare a Final Forward Look Report to be submitted to ESA to advise its High-level Science Advisory Committee.

During the duration of the information gathering process, it became apparent that the complexity of risk assessment on such a fluid topic as technological evolution was beyond the scope of the effort. The TECHBREAK report will therefore fulfil all the objectives, except conducting a thorough risk analysis. Some elements of perceived risk regarding the technological development landscape in Europe are included in the report, together with suggestions on how to navigate in this landscape, as communicated to the TECHBREAK team by prominent actors in the various technological areas.

In conclusion, the TECHBREAK report cannot serve (and it was not meant to do so) as a definitive guide on which exact technologies should be developed for future space missions. What the report is designed to do is to inform on and flag up the main developments in various technological and scientific areas outside 'space', that might hold promise for use in the space domain. The report does this by identifying the current status of research for each domain, asserting the development horizon for each technology and providing some entry points, in the form of key European experts and institutions with knowledge of the domain. Since the focus was 'breakthrough technologies', the technology list is comprised of mostly recent and often borderline scientific advances. Thus, the TECHBREAK technology list can serve as an indicator of technologies that could be utilised in space missions beyond 2030.

2. TECHBREAK Activity

The project started concretely in early 2010 with a definition phase during which the Scientific Committee elaborated a foresight strategy and methodology with the support of an external foresight consultant from the ISI Fraunhofer Institute (Dr Kirsten Cuhls). Additionally, experienced ESA personnel were interviewed, regarding the pragmatics of technology development and planning in the various ESA programmes.

As a result of these consultations, some of the objectives that were mentioned in the previous section were re-assessed and it was decided jointly with ESA to concentrate on the identification of relevant non-space technologies for infusion into the space sector that had not been known nor used so far in the space context, and might hold promise for this sector. An important point therefore was to identify the right level of granularity at which the availability of such technologies could be assessed for potential spin-in. The concept of Key Enabling Technologies (KETs) was chosen to maximise commonalities with the European Union (EU) and synergies with the other ongoing activities at ESF.

For the purpose of this foresight exercise, these fields were grouped as follows:

- Nano- and microelectronics (NAMI)
- Photonics (PHOT)
- Advanced materials (ADVM)
- Biotechnologies (BIOT)
- Nanotechnologies (NANO)
- Robotics (ROBO)
- Biomimetics (BIOM)
- Energy and propulsion (ENEP)

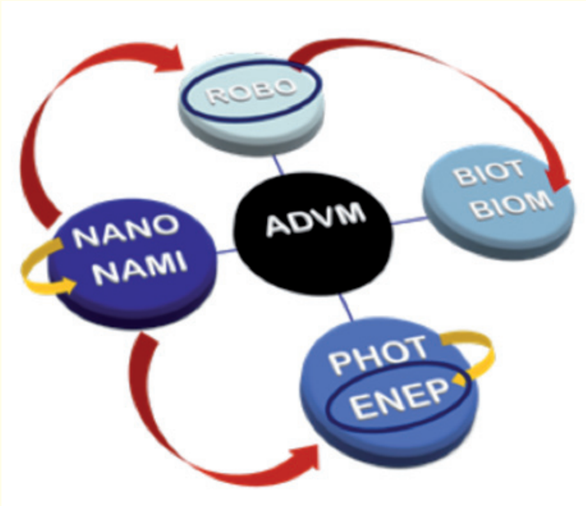


Figure 1. Relationship between key enabling technologies

This classification was used in organising thematic workshops, with invitations to prominent researchers, institutions and policy makers in those fields.

After several workshops in the various KET areas, the TECHBREAK team undertook one-to-one interviews with prominent European researchers who are active in those areas. These interviews provided several insights to the KET fields as well as several, often different, viewpoints on technology transfer and development across various disciplines.

The output from the interviews and the workshops was catalogued and expanded further, with bibliographical research, in order to identify the most prominent technologies for the TECHBREAK report. The following sections expand on the initial inputs to TECHBREAK and present a brief synopsis of the TECHBREAK workshops.

2.1 TECHBREAK inputs

In addition to the methodology definition report provided by ISI Fraunhofer, two main inputs into the foresight exercise were commissioned, to the European Space Policy Institute (ESPI – Ms Christina Gianopappa) and to ESA's Advanced Concepts Team (ACT).

2.1.1 Reports

These two reports (figure below) were helpful in (a) framing the exercise, and (b) deciding which technological areas, and at which level of granularity, the foresight exercise should focus on. It was decided that the project would make use of the classification of disciplines under the broad headings of 'Key Enabling Technologies', as identified in 2009 by the European Commission, i.e., nanotechnology; micro and nano-electronics; photonics; advanced materials; and biotechnology.

Other areas such as energy, robotics, biomimetics or advanced propulsion and, more generally, materials science were also addressed. These KETs are relevant at various levels for EU's 'Grand Challenges' (Energy, Healthcare and Security). Those key technologies already have a strong or a developing industrial base, should receive considerable funding in the future and would be the target of the bulk of Horizon 2020 funding. Therefore, strong ties between ESA and the main players and innovators in those key fields would be of significant benefit. The Key Enabling Technologies will be defined in the main part of the report.

A summary of the key findings of the ESPI report is presented here and should be considered by ESA, and even the EU:

1. The Key Enabling Technologies identified by the EU as being nanotechnologies, micro and nanoelectronics, advanced materials and biotechnology, should be considered comprehensively by ESA's research and development programmes. In this regard, Information and Communication Technologies (ICT) should also be considered, creating the 'ESA Enabling Technologies' concept. These categories are essentially very broad and specific subcategories should be identified, in consultation with space and non-space experts in these fields, in order to identify the ones most relevant for the space sectors to be able to develop coherent roadmaps.
2. At low Technology Readiness Levels, such new technologies do not need to be developed exclusively by space funding schemes. This may allow the utilisation of funding from the non-space sector by jointly investing in the KET's building blocks.
3. Public and private partnerships should be set up for co-financing research and development in Key Enabling Technologies, since they require large investments that ESA alone would not be able to afford.
4. ESA should proceed to apply for participation in research and technology development under the non-space components of the Framework Programme. This participation, by performing research and development in ESA laboratories, should be enhanced.
5. An effective technology watch 'Technowatch' mechanism is necessary in order to be able to identify new and disruptive technologies early enough; a Technowatch that can facilitate spin-in, spin-out and spin-together. ESA does currently have mechanisms which are used as observatories for following science that is likely to produce technology. This could be institutionalised with clear targets and responsibilities in a more integrated model. The possibility of having a Technowatch independent from ESA or jointly with other technology watch institutions should also be considered. It is suggested that a Technowatch should be an independent body as these are seen as more credible when they are not governmental agencies or those that conduct the research.

Figure 2. ESPI and ESA-ACT input reports to TECHBREAK

The ESA Advanced Concepts Team provided insight to very low TRL technologies that have the potential to become 'game changing' technologies in the future. The input proved useful in identifying experts in various fields who could further elaborate on these technologies. The following areas were highlighted in the report, as topics with significant 'breakthrough' capability:

1. High-fidelity dynamical simulation and optimisation
2. High precision formation flying

3. Autonomous manoeuvres for low-thrust deep space mission
4. Pulsar navigation
5. Relativistic reference systems
6. Application of Bose-Einstein condensates
7. High precision spectroscopy
8. Diffractive focussing
9. Metamaterials
10. Soft matter
11. Structural biomimetics
12. Neuromorphic electronics
13. Bionics
14. Neural engineering
15. Truly internally motivated robots
16. Multi-agent robotic systems using GPS
17. Multidisciplinary Design Optimisation (MDO)
18. Space Nuclear Power Sources (NPS)

2.2 ESA interviews

Another input into the project was the ESF survey that targeted ESA experts regarding breakthrough technologies and ESA technology development programmatics. The following questions were forwarded to the ESA experts:

1. In general, do you believe that science teams tend to moderate their ambitions because they fear their proposals might not get selected for technological readiness reasons?
2. If not, what do you think are the main reasons for gradual – not breakthrough – technological evolution in space missions (please prioritise)?
3. From your experience of experiment selection processes in your field of competence, were there scientifically highly-ranked proposals rejected because of their low technological maturity and/or high risk of cost overruns?
4. If yes, can you provide some level of details concerning such 'case studies'? For each case what do you think was the main reason for rejection: TRL? Cost? Please detail.
5. Have missions been selected despite a low TRL or high risk of cost overruns? Please detail.
6. Do you think this approach/model (technology push/pull) is still valid? Within which boundaries?
7. Do you believe that this set of KETs can adequately capture the concerns addressed by this foresight exercise? Which of these KETs should in your view become of strategic importance to ESA through, e.g., partnerships with public and private entities, to co-fund R&D that ESA alone cannot support?
8. Is there a continuity of developments from the advanced stages to fully operational systems? Do we have in Europe the appropriate tools for maturation of technologies (cf. the DARPA model in the USA)?
9. Do you believe that this set of KETs can adequately capture the concerns addressed by this foresight exercise? Which of these KETs should in your view become of strategic importance to ESA through, e.g., partnerships with public and private entities, to co-fund R&D that ESA alone cannot support?
10. Are there specific sectors that you think should become involved in partnerships with ESA, e.g., energy, automobile, healthcare, etc?
11. In your domains and in recent years, have you identified ideas/cross-domain topics that scientists have not necessarily thought about but could lead to innovative scientific developments?
12. More generally, do you think the innovation potential and experience of European industry could be more deeply exploited? Do you have further suggestions for future improvements and new mechanisms?

The following experts responded to the survey:

- Pierluigi Silvestrin (Earth Observations)
- Scott Hovland (Human Space Flight)
- Alain Pradier (Human Space Flight)
- Rafael Lucas Rodriguez (Navigation)
- Fabio Favata (Science Planning and Community Coordination)

Interview synthesis

There was general consensus amongst the ESA experts that the scientific communities are not technologically conservative when it comes to mission concept proposals. It is important that there is a distinction between the two-step approach to a call. Often, the experience that the community is 'technologically conservative' in mission proposals is based on a misunderstanding. The scientific community is invited to be imaginative in looking for answers to science challenges or techniques of conducting science. The selection is made on the basis of multiple criteria established at the beginning of the call, which normally emphasise the scientific value of the mission rather than technical-programmatic feasibility.

Furthermore, the criteria are finally applied by a group of scientists, within the Science Advisory Committee, whose concern is primarily with the scientific excellence and answer to the challenges than to the technology readiness. The technological readiness itself is evaluated by the Agency and presented to the committee.

The second step includes the selection of the industrial consortium that will implement the selected mission. The choice is made on the basis of the system requirements elaborated during the Phase 0 and A activities. To achieve these, different technical solutions may be possible and obviously industry tends to look for those solutions that minimise their risk. This is the reason that sometimes missions may be driving towards technologies that are less 'frontier technologies', but nonetheless the achievement of the system requirements is a must and strong innovation is in general required at least in the payload area.

Despite the risk aversion of industry, the science teams strive to formulate demanding scientific objectives. Normally, TRL levels do not come into consideration during the proposal submissions. Of course, there are always exceptions. A user community that is focused more on applications, such as a GNNS payload for aviation, might be *de facto* conservative in the proposals put forward, in order to accommodate the real constraints in the capabilities of the system. For scientific applications, the way of thinking is less constrained.

There are, of course, proposals that are rejected for too low TRL and/or cost estimates above the limits set by the Calls. These two elements are in fact coupled: a low TRL means a long development time and high risk, which requires adding large margins in cost estimates. There is also an aspect of fairness to proposers when missions that are way above the cost limit are rejected: those proposing such expensive missions can claim stronger scientific returns than those who have properly considered the cost aspect in their proposals as required by the Calls, but it would obviously be unfair to privilege those who have not observed the rules of the Call (which are discussed and approved by the Programme Board). All considered, the ESA Calls aim at the best ratio 'science-return per euro', and the level of technological innovation is linked to the imposed budgetary and schedule constraints, which vary between Calls.

The view that technological breakthroughs do not happen was considered partly inaccurate, as there have been missions that can be considered showcases of breakthrough technologies and concepts. The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission is a prime example. Nevertheless, there are numerous factors that do influence a space mission and prevent breakthrough missions from being the norm. These factors were identified as:

Long development time: The development of space projects has a very long time span. From inception to operation it can easily take 10 years. The long time frame might create the impression that the technologies are not cutting-edge, as a technology which was a breakthrough at the time the project was initiated might be perceived as old when the project is completed.

High costs: The costs of developing and launching space projects are very high, so the risks/costs of failure have to be minimised. This would mean that the use of off-the-shelf technologies (or as close as possible) would be preferable to the development of a new breakthrough technology which is untested.

Organisation of space projects: This is related with the high costs of space projects. The project organisation needs to be rather rigid in order to guarantee the success of a mission. The project baseline and the associated technology are gradually frozen at each milestone of the development process (Phase A,B,C,D). Once a milestone has been passed, it is very difficult to go back to reconsider decisions since this would lead to delays and cost overruns. A more flexible structure of organising the project would be more suited to encouraging technology breakthroughs, e.g., more collocated teams, lesser number of distributed subcontractors.

Not sufficient new needs: For a new technology to be developed, the needs of the project should be sufficiently different from the needs of past projects. Incremental science can be operated with incremental technology developments.

Few missions: The number of missions is limited; therefore the opportunity to experiment with new technologies is also limited.

R&D investment effort in low TRL emerging technologies is often not adequate to bring them to an acceptable level for project implementation in a timely way.

Ultimately, the reason that breakthrough missions are not often implemented is closely related to the management of risk. The ExoMars mission can serve as an example: one of the main scientific objectives was to detect traces of past or present life on Mars. The Life Marker Chip (LMC) instrument was proposed by scientists at the University of Leicester and Cranfield University. It was supposed to utilise biotechnology measurement techniques to detect specific molecules that may be associated with past or present life on Mars. A TRL assessment gave rise to serious concerns related to a too low level of technical maturity which made a timely implementation in the ExoMars mission quite questionable. Despite its very high scientific relevance and strong political support in the UK, the LMC was dropped out.

TRL level and cost overruns are tightly linked. Misestimating the maturity level of the technology or the inability to push the level from TRL 4 to TRL 6 in a timely manner would lead to cost overruns as the mission is either delayed or a substitute technology is sought out.

Despite the major obstacle that the maturation of technologies poses for space missions, it might be difficult for a solution to come from broad R&D efforts. Space technology R&D is very expensive. A vast number of disciplines have to be addressed, and the resources devoted to this are far too limited. Sometimes efforts are made even less effective due to conditioning by industrial-political aspects (e.g., in GSTP). Under these conditions, considering that there are *a priori* countless R&D activities that could be pursued, a technology push approach risks under-sampling the possible directions of technological developments, with the risk that the technologies actually needed to implement the missions are not there (at the right TRL) when required. There is also the risk that many parallel routes are pursued in a field without reaching adequate TRL in any of them (examples can be given, e.g., in the area of propulsion). Nevertheless, many applications today are a result of a technology push and an effort to make the users aware of the many possibilities of the new technology.

The possible collaboration in the R&D effort with the EU R&D efforts in the various Key Enabling Technologies was seen positively, in order to benefit from the much larger investments in other sectors. The innovation potential of European industry could be better optimised and exploited. The sole definition of strategic technical R&D themes along with a lean 'hands-off' management approach is not deemed the most effective way to drive the current significant EU R&D effort to substantial results having strong relevance for future space applications. The current state of ESA-EU relationships in the area of advanced technology development is far from ideal to really ensure a good return of investment. A more sustainable political commitment to supporting the R&D industrial sector in Europe might eventually lead to a game changing situation, provided that the technical management of European R&D effort having relevance for space applications is appropriately delegated to competent entities.

2.3 Thematic workshops

The original intention was to organise thematic workshops in at least four domains, i.e., ADVM, NAMI, PHEP and BIOT. A total number of five workshops were organised:

- Scoping workshop to frame the activity and decide on goals and work plan; this workshop took place before the official start of the activity and brought together ESA, ESF and EC representatives.
- Kick-off conference (Brussels, 29-30 November 2010) – 27 attendees, with experts in various KETs.
- Advanced Materials thematic workshop (Obernai, 27-28 September 2011) – 10 attendees.
- Multi-thematic workshop (Brussels, 22-23 February 2012) – 13 attendees.
- Photonics workshop (Barcelona, 27 March 2013) – 15 attendees.

In addition to the events detailed above, the TECHBREAK Scientific Committee met six times during the lifetime of the project. It is composed of the following individuals, supported by ESF (Dr Jean-Claude Worms and Dr Emmanouil Detsis as of December 2012):

- Dr Martin Cullum (ESO, DE, retired)
- Professor Colin Cunningham (STFC, UK)
- Dr Paul Kamoun (Thalès Alenia Space, FR)
- Dr Jean-Jacques Tortora (EUROSPACE, FR)
- Professor Jean-Pierre Swings (University of Liège & ESSC Chairman, BE)

Finally, a 'Review Meeting' was organised in Brussels, on 31 October 2013, in order to finalise input to the TECHBREAK report. The meeting participants included, apart from the TECHBREAK committee, several experts in European KETs. A list of all participants in the TECHBREAK workshops can be found in Appendix E.

2.3.1 Multi-thematic workshop highlights

This workshop brought together 13 participants including the TECHBREAK Scientific Committee (3), ESF and ESA staff (2). The participants were experts in the fields of nanotechnology, biotechnology, propulsion and advanced materials. Photonics and Energy were not covered at that event.

Several generic issues were discussed, and in particular:

1. Spin-in technologies for the space sector;
2. Future dedicated calls by ESA to target specific communities;
3. Interdisciplinary workshops.

The main outcome from this workshop and from the discussions led in the Scientific Committee was the definition of five **Overwhelming Drivers** at the core of this foresight exercise. During the workshop presentations, several interesting technologies were mentioned that provided the first identification with

Table 1. Space Overwhelming Drivers, as initially defined in the TECHBREAK multi-thematic workshop, together with suggested solutions

Problem	Solution
Longevity in space	50 years overall lifetime? Or 50 years in space without return to earth?
Tear and wear due to harsh conditions	Frequent control, maintenance and repair: non-destructive material analysis, miniaturised process sensors and remote control, process simulation and modelling, modular construction, remote module exchange Rapid turnover strategy: in space production on demand; microreactor technology; DNA as template
Limited space for supply storage	Generic (micro)fabrication technologies, fabrication on demand: e.g., synthetic biology; DNA synthesis and cell-free protein production, tissue engineering) e.g., for probes (analytics, diagnostics), pharmaceuticals, pesticides. Bioproduction of feed, food (aquaculture, horticulture, fermentation, tissue engineering); closed loops for air, water, remediation and waste recycling; engineered agro-ecosystems and food webs
Compensation for underused abilities	'enviromimetics' – drugs which mimic environmental stimuli on metabolism/physiology (e.g., physical activity, gravity, biorhythms, magnetic fields), mood enhancers

interesting KET domains (Table 1).

The discussions at the kick-off conference led to a mind-mapping of technology sub-domains (see Table 1) of potential specific interest to the space sector, using the eight fields defined at the beginning of section 2. The mind-mapping exercise isolated the KET areas that have the potential to produce ground-breaking results. This exercise produced the first level of granularity for TECHBREAK and identified the interesting fields in the key enabling technologies.

2.4 Space needs and challenges

The conclusion of those discussions was that this foresight activity should focus on defining the needs and challenges of the space sector in relation to the potential offered by non-space critical technologies in these domains. The needs and challenges should ideally be defined and then mapped against technological sub-areas to create a series of matrices, ranked in terms of their space relevance.

These space needs and challenges were then further refined at the ADVM thematic workshop, and transformed into specific areas of potential interest for future space missions, as listed below.

1. Large structures
2. Miniaturisation
3. Propulsion
4. Systems longevity/self-repairing capacity
5. Energy supply: reach a theoretical maximum for solar power conversion
6. Sample collection and handling
7. Search for life
8. New environments/bioengineering
9. Communication
10. Cryogenics

The discussion and analysis of this specific case led to the selection of four main problems and solutions that are depicted in Table 1. These became the new space needs and challenges for that particular long term mission scenario, and fuelled the identification of the technological sub-fields to be considered.

Finally, and most importantly, the discussion concerning the identification of problems and solutions led to focus the discussion around the concept of 'Overwhelming Drivers' for space research and exploration, i.e., long term goals that can be transposed into technological development goals (cf. section 3).

2.5 Expert interviews

After the conclusion of the thematic workshops, the TECHBREAK committee engaged leading researchers in Europe in one-to-one interviews, in order to gauge their expert opinion in the technological areas that could potentially be relevant to the space sector. The concept of the Overwhelming Drivers was used for the first time, in order to stimulate the discussion. The following list of questions was provided to 20 experts (the names and contact details can be found in Appendix A).

2.5.1 Interview question list

a. Can you please provide a short summary of your research interest and activities?
b. In your field(s), what do you think the most important developments will be in the next 5 years? In the next 10 years? Are there any 'game-changing' technologies that you foresee?
c. Are there any niche technologies in your field that have the potential to play an important role and perhaps they are not known to the space sector?

d. How do you think the landscape of research in Europe will be shaped in the decades to come in your field(s)? Which are the institutions/companies that will be prominent in the next decades in your field? Are there any major research initiatives that we should be aware of?
e. Whom else should we talk to next?
f. In your field(s), what is the potential for solving any specific Overwhelming Driver for Space *(refer to accompanying document)*? How would you rate the relevance?
g. Regarding the identification and 'spin-in' of breakthrough technologies, what should European Space Agency do to reach out to new communities and research fields? Are there good and adaptable models at the international level that could be used in your field? How?
h. What would be the most interesting ways for researchers in your field(s) to get involved in European space projects?

2.5.2 Interview synthesis

The interviews conducted with additional experts helped focus the TECHBREAK technology search to the areas that are at the forefront of the European research effort. It also provided identification of potential breakthrough technologies, as indicated by the world class experts working daily with these technologies. The main output of this exercise can be seen in the following chapters of the TECHBREAK report, where the technologies themselves are presented.

The interviews were also designed to inquire about ways of collaboration between ESA and the various research communities that the experts believed to be the most appropriate for their fields. A synthesis of the main points extracted from the interviews is given in the following paragraphs.

Structure of the research landscape

It is a general trend that the large (international) collaborations will be the predominant way to maintain and further increase the pace of research activities. Furthermore, the applicability to and impact of the societal value of the research proposal is quickly becoming the most significant factor in research funding grants.

Another significant trend in many research fields is to use a cross-disciplinary approach. This is exemplified by the FP7 funded THESEUS exploration roadmap that stressed the need to integrate many aspects from habitat design to habitat atmospheres and life support systems when man is subject to extreme conditions of stress and in order to maintain their health, which is the ultimate goal.

What this effectively means is that it is important to foster flagship projects to bring Europe to a sufficiently competitive position. Regrouping of forces from laboratories and industries is needed in order to strongly invest in a small number of key directions. There is a need to increase the role of large centres with shared resources and create international centres though agreements between countries. The more different technologies at different stages of maturity can be combined, the more Europe will have a competitive advantage.

The resulting projects might be too big for a single funding entity. ESA must, therefore, pass from a critical framework (sanction) to the framework of accompaniment in large projects. Europe masters key technologies but fails to appropriately disseminate them. Developments in the space domain will also generate spin-offs in other domains and create a virtuous circle. Conversely, the space domain can attract other domains and thus support breakthroughs that SMEs would not be able to sustain by themselves.

Motivation for technology development

Several options were presented, with the request for significant and sustainable funding being the most prominent motivation for researchers (if not the most original). Other options include:

- Prizes to reward best cooperation between space and non-space sectors. Non-space industry is not motivated to take part in a programme that will only go to market within 20 years; the prize would serve to foster cooperation despite the long maturation horizon.
- Identify laboratories (non-space) and allocate funding and specific problem-solving tasks to them. The various scientific disciplines exist in their own right and they know very well who does what in their own field. They should be able to manage the task of gathering the appropriate researcher to tackle the new problem.
- ESA could get involved with researchers and help them document what that impact could be with respect to the space sector. That would create an incentive for the researchers to work on research that could have space application, as this might improve their grant applications. As mentioned before, most non-space researchers are not familiar with space-related boundary conditions, or with the potential impact of their research if applied to space.

Existing examples of successful spin-off models

Examples of spin-off models that have worked well in the energy, medical and information technology domain can be found within the Fraunhofer institutes, which create a large number of patents and companies. In the Japanese model, the government launches programmes with all industrial partners and when the programme is mature, each partner goes its own way, but common laboratories exist for several years. In the CSEM Swiss model, several industrial partners invest in an institute to develop a specific technology. In France there was a similar system with the watch-making industry in Besançon.

Risk management in technology development

High level technology is correlated with high risks (financial and delays). There are three main players that can potentially bear these risks: industry, scientific programmes and technology programmes. The first two options are probably not the most appropriate to do so. First, industry can only bear assessable risk and a 'potential breakthrough' represents an undefined risk. Secondly, scientific programmes must be secured in order to keep up with timeline and budget. Risks should be integrated in the science policy itself and on the programmes. That only leaves the technology programme development agencies as the bearers of the technology development risk.

Most technology programmes are focused on early stages of development. What is missing is another kind of programme to accompany technology developments, in order to get the technology to the right level of performance. These technology maturation programmes are missing in Europe. The most prominent example is possibly in the USA, with DARPA playing a major, if not the leading, role in that regard.

Niche technologies

Niche technologies must be kept alive in small groups or SMEs of a few dozen people so there is an important analysis to identify precisely what could be usefully done by SMEs and what can be done exclusively by large companies.

3.
Overwhelming Drivers

One of the main problems that the TECHBREAK committee encountered during the various workshops and other communications with European scientists and experts (non-space), was how to actually explain what the problems are that ESA in particular and the space industry in general are facing. This is obviously an important issue when trying to identify technologies that may offer potential spin-in to the space sector.

Space is often quite cut off from other technological areas, either due to perception, distance or design. Even everyday interaction with space infrastructure and processes happens in a way that is opaque to the everyday user. A driver consulting the car navigation display in order to identify the best possible route or even a researcher who uses the latest, extremely accurate Earth geoid doesn't necessarily understand what it takes to put a Galileo satellite in orbit or the intricacies of designing GOCE able to fly at very low altitude.

One of the main outcomes of TECHBREAK was the definition of five 'Overwhelming Drivers' for space. These drivers represent the main areas where technological improvements are needed in order to be able to generate breakthroughs in space capabilities. The drivers also served as a brief introduction to the space environment and space operations for non-space experts and acted as a stimulant for the identification of potential helpful technologies. These drivers were the communication tool that the TECHBREAK team utilised for bridging the knowledge gap between space and non-space experts. Their definition and utilisation aimed at providing the 'food for thought' stimulus that might result in a spin-in idea, from a KET field into the space domain.

Beyond this goal, however, it is believed that these five Overwhelming Drivers could be used throughout ESA's Directorates as a novel categorisation of programme concepts and useful red thread to guide reflexion about future missions and related technological maturation.

The following drivers were identified:

Table 2: The Overwhelming Drivers for space (ODs) that serve as an introduction to the looked-for solutions from other scientific and technological fields

	Overwhelming Drivers
1	Reduce mass, maintain stiffness
2	Build a spacecraft and space missions that can last 50 years
3	Deploy a 30m+ telescope into space (assembling, deploying, self-supporting, positioning, maintaining)
4	Autonomous geophysical survey of planets
5	Enable humans to stay in space for more than two years (Mars mission)

Initially, there was a sixth driver, 'Advanced Propulsion'. Despite the obvious significance of propulsion for space (launch and in-space propulsion included), it was either:

a. Difficult to frame the complexities of the issue in such a way as to readily identify connections with KET areas; or
b. Difficult to have access to the industrial information necessary, in order to make the connections;
c. ESA is in the forefront of the development of most of the technologies.

For these reasons, advanced propulsion has not been explicitly mentioned as an overwhelming driver for space.

Overwhelming Driver 1:
Reduce mass, maintain stiffness

“I always figured we were born to fly, one way or other, so I couldn’t stand most men shuffling along with all the iron of the earth in their blood. I never met a man who weighed less than nine hundred pounds.”

Ray Bradbury, *Twice 22: The Golden Apples of the Sun*

3.1 Reduce mass, maintain stiffness

The core problem of access to space is that the launch cost is too high. Every kilogram contributes to the total cost on the order of 5,000 – 20,000$, depending on the vehicle and desired orbit. Given current launcher technology, there is no indication that there will be significant change in the near future. Reducing the weight of spacecraft is therefore a critical goal.

Space structures account for a significant portion of the mass budget of a spacecraft and serve the role of holding the instruments in place. It is therefore important that not only are they lightweight, but that they also provide a stable platform for the scientific instruments by having the appropriate stiffness. Heavy bulk material is also needed for radiation shielding, which also adds to the mass budget.

The goal would be to identify materials and technologies in order to reduce the overall weight of the spacecraft bus. Primary targets are the large spacecraft structures such as booms and masts. It is important for such structures to be able to maintain their stiffness, despite potential reductions in mass. Improvements would also be accomplished by reducing the weight of cabling in a spacecraft, by replacing or completely eliminating current cabling materials with other, lighter cables or even optical or wireless links. The mass of the cables accounts for a significant percentage of the spacecraft dry mass.

The problems stemming from this Overwhelming Driver can be seen in the following table. The third column codifies the potential solutions and will be used in a later chapter to map potential solutions to available technologies.

3.2 Build a spacecraft and space missions that can last 50 years

Space environment is a harsh environment in which spacecraft need to operate for long periods of time. A lifetime in excess of 50 years might not be an unreasonable requirement for a spacecraft. There are two main reasons for this time scale. The first reason is operational: for missions to the outer solar system, it might be necessary to establish such a long mission timeline (for example, Voyager 1 has been operating for 36 years and the New Horizons spacecraft has a nominal operations timeline of around 20 years). The second reason is financial: with the very high costs associated with some of the space missions, it is logical to demand that the asset can be utilised over very long time spans. In order to achieve this, space systems need to be durable, reliable and with redundant design and/or the ability to self-repair.

It must be noted that this is in contrast to ground based instruments. For example, ground based telescopes are build with lifetime expectations of comparable length (for example, ESO's VLT had a designed lifetime of 25 years). The fact that instruments can be replaced on the ground raises the issue of *technology* obsolescence higher than that of instrument lifetime. The main issue in a space based observatory, with a mission profile that will disallow any upgrades in space (outer solar missions), is preventive maintenance, since the technology is frozen for the duration of the mission, with the possible exception of software upgrades.

Main sources of 'wear and tear' of a spacecraft are temperature fluctuations and radiation, in particular for spacecraft operating outside the protected

Table 3. Reduce mass, maintain stiffness Overwhelming Driver problematic areas and potential solutions

Problem	Potential Solution	Code
Structural materials are heavy	Replace materials with new, lighter materials with similar or better performance	OD1.1
	New structural designs that use less materials	OD1.2
	Lightweight, active structures	
Electrical cables are heavy	Replace cabling materials with lighter ones	OD1.3
	Eliminate cables	OD1.4
	'Print' cables on the structure itself	OD1.5
Radiation shields are heavy	Identify novel materials for shielding	OD1.6
	Identify novel techniques for radiation shielding	OD1.7
Efficiency	This is a generic solution that indicates the decrease of system mass due to efficiency gains (improved techniques, new materials, etc.) and is not relevant to other potential solutions	OD1.8

area of the Earth magnetosphere. Solar radiation (the solar wind) and cosmic rays deluge the spacecraft with charged particles constantly. Solar and cosmic radiation in space are deadly for biological tissues as well as electronics and materials, resulting in unavoidable degradation and embrittlement, which accumulates over time. Additionally, during its lifetime the spacecraft can often operate under extremely cold conditions or direct sunlight that increases the temperature significantly or even operate with high temperature gradients due to one side being in sunlight and the other in shadow. Materials that can withstand the high fluctuations and temperature gradients are necessary in order to protect the payload and offer an operating environment for the instruments.

Another significant problem for spacecraft is operating in the vacuum of space. Since the ambient pressure in the operating environment is extremely low, structural materials experience outgassing or sublimation, which may result in mass loss over a significant period of operation. The most direct problem arising from this issue is the deposition of the evaporated material, which can be hazardous for sensitive optical or electronic surfaces. Mass loss particularly affects plastic layers and oxide coatings. As a consequence of this, traditional lubricants are not used in space, since their high vapour pressure will result in significant and rapid mass loss. Solid lubricant coatings and low-volatility oils are used instead.

Another source of structural damage is the space debris that orbit the Earth. Whilst large debris are tracked and commands can be given to the spacecraft to avoid them, there is a significant flux of small debris that impact the spacecraft. Given the high-velocity collisions due to the high orbital velocities, even tiny particles can cause significant damage. For spacecraft in Low Earth Orbit (LEO), the attenuated presence of the Earth's atmosphere causes collision between the spacecraft and oxygen atoms that results in significant erosion of surfaces, leading to significant degradation.

Fifty years is a long time for a machine to operate, even if it were not in space. Mechanical failures are to be expected due to the prolonged use of systems, without a direct connection to radiation damage or temperature fluctuations necessarily. The ability to self-repair may be necessary, in order to maintain a functional system.

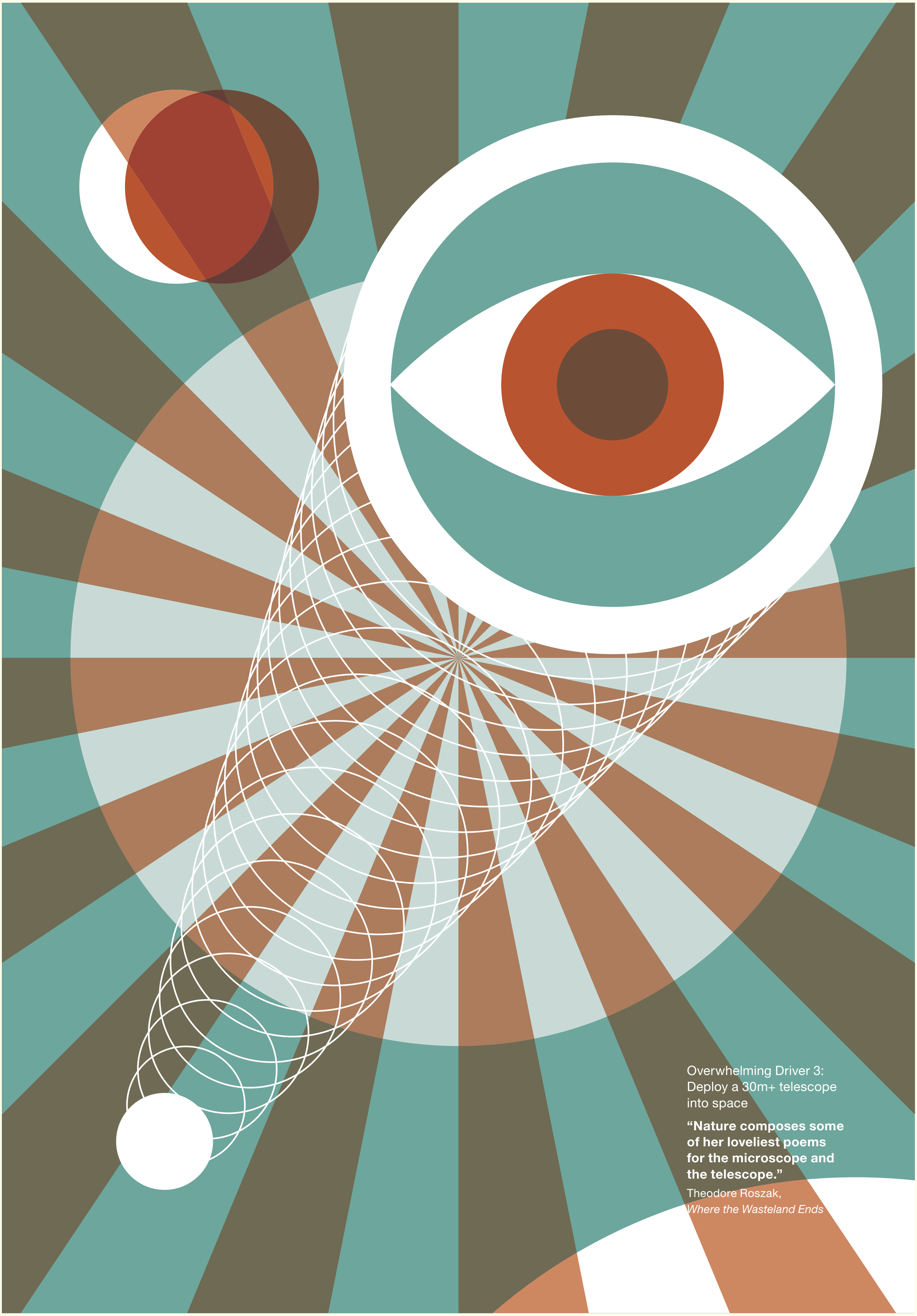
There are three ways to circumvent the aforementioned problems: materials that can withstand the harsh conditions, the ability to repair in space or the ability to replace damaged instruments and materials.

Finally, and perhaps most crucially, it is important to be able to simulate and test the behaviour of the spacecraft, taking into account the long timeline and doing so within a reasonable cost and timeframe. If the goal is to have a spacecraft that lasts 50 years, it is important to be able to model the behaviour of the craft after decades in space. Laboratory testing techniques need to evolve in order to be able to simulate the ageing of a spacecraft accurately and simulation software must be able to factor such long timescales into the designing phase.

Table 4. Build a spacecraft/space missions that can last 50 years Overwhelming Driver problematic areas and potential solutions

Problem	Potential Solution	Code
Temperature cycling	Materials that can withstand high temperature gradients	OD2.1
	Advanced thermal control	OD2.2
Radiation	Novel shielding techniques that don't rely on bulk material shielding and can provide protection for longer periods of time	OD2.3
Degradation, erosion, mass loss	Automatic repair of damaged material. Self-healing materials and structures are needed	OD2.4
Mechanical failures	Self-healing mechanisms, automated repairs, design redundancy	OD2.5
	Modelling and accelerated life tests	OD2.6
Fuel storage	The storage of hydrogen is made more efficient. Hydrogen is extremely difficult to store for long period of times. One solution would be the development of a polymer tank to store hydrogen	OD2.7
Improved energy sources	Being able to provide energy for a long period of time is a problem that will require not only the capability to prevent/repair degradation for the involved systems (i.e., degradation of solar cells), but will also require advances in the efficiency of existing power production systems in order to reduce weight or size or both	OD2.8


Overwhelming Driver 2:
Build a spacecraft and space missions that can last 50 years
“Fifty years,” I hackneyed, “is a long time.” “Not when you’re looking back at them,” she said. “You wonder how they vanished so quickly.”
Isaac Asimov, *I, Robot*


Overwhelming Driver 3:
Deploy a 30m+ telescope
into space
“Nature composes some of her loveliest poems for the microscope and the telescope.”
Theodore Roszak,
Where the Wasteland Ends

3.3 **Deploy a 30m+ telescope into space (assembling, deploying, self-supporting, positioning, maintaining)**

Telescopes and their instruments are large and complex, regardless of whether they are based in space or on the Earth. Especially for ground based telescopes, there is a trend of building bigger telescopes, as the enabling technology becomes available. The current largest ground based telescopes utilising mirrors are in the 10m diameter range [the Keck telescopes (10m) and the Gran Telescopio Canarias (10.4m)], with future instruments designed to reach a mirror diameter of 25m (Giant Magellan Telescope in Chile) or even 40m, with the aptly named European Extremely Large Telescope, also to be located in Chile.

In order to continue the quest for answers to the secrets of the cosmos, future space missions will also require building and operating very large structures/observatories in space. Using the current and planned launch vehicles, putting a 30m telescope in space would be a challenge, due to the limited volume available in the fairing. Large mirrors are very difficult to construct, transport into space and maintain in optimal condition. With a mirror of 30m+ in diameter, novel techniques need to be developed.

There are several conceivable ways of creating a large telescope in space. The traditional way is to use a structure with finished mirror segments that can be packed inside the rocket fairing and then unfolded and aligned once they reach their destination. Another approach could be to use a flexible mirror that would be inflated or unfolded in space and rely on active control mechanisms to provide the required optical figure. The mirror surface will need to be very smooth on a small scale, but not necessarily passively accurate on a large scale as with current space telescopes.

Although a space telescope is complex, its function is largely independent of the science undertaken. The ancillary instruments, on the other hand, are very science-specific. Several instruments would be needed and these might be exchanged at intervals throughout the life of a telescope. A formation flying concept in which the telescope and instrument are free-flying is therefore extremely interesting. The telescope could switch between several free-flying instruments. New self-contained instruments could be launched and parked as required and defunct ones deorbited. That ability would enable the space based observatories to 'decouple' the main mirror from the detectors, since the lifetime of mirrors tends to be longer than the detectors'. A further advantage of a free flying telescope is that the primary mirror can be of much longer focal length which is easier and cheaper to manufacture and align.

Maintaining the shape and accurate control of such a large structure is nevertheless challenging, especially so since the requirements for astronomical instruments call for extreme precision. A large telescope in space must be diffraction limited even at visible wavelengths if it is to remain superior to large ground based telescopes. Even though there will be no atmospheric turbulence, (slow) active optics will still be necessary to achieve diffraction limited performance. Probably a two-tier process would be advantageous: although instruments will generally need to be 'adaptive', correcting the large scale deformations of the primary mirror within an instrument may be difficult due to the large dynamic

Table 5. Deploy a 30m+ telescope into space Overwhelming Driver problematic areas and potential solutions

Problem	Potential Solution	Code
Assembly of large mirrors in space	Flexible or foldable mirror and support structure, to circumvent volume restrictions on launch	OD3.1
	Formation flying of parts (no support structure). Technologies such as micro-thrusters and laser metrology for fine position control and precise formation flying. Formation flying might be achieved by utilising other forces to maintain position, such as ferromagnetic forces	OD3.2
	Robotic systems for the assembly of structures in space	OD3.3
	Novel packaging and deployment techniques based on biological organisms	OD3.4
Maintenance of large mirrors in space	Robotic systems for the maintenance of structures in space	OD3.5
	Technologies for maintaining the optical surface quality of large mirrors in space	OD3.6
	Advanced coating materials to prevent degradation	OD3.7
Detectors	Energy sensitive detectors with minimum cooling requirements, particularly in the IR and visible ranges, to enable simple, low spectral resolution 2D imaging	OD3.8
	Plasmonic optical systems and astrophotonics instrument concepts to reduce both the mass and size of space instruments	OD3.9
	Advanced interferometers of ultra-compact dimensions (nanotechnology)	OD3.10

range required. A telescope with an active primary to correct large scale wavefront deformations coupled to an instrument that takes care of small scale deformations would probably be a more optimal solution.

Maintaining the surface quality of an optical mirror in space is also an important aspect. Although the loss of reflectivity of the mirror coating in space should be less severe than for ground based telescopes, an increase in surface scattering due to bombardment of micro meteorites, atomic oxygen, etc. will be more serious. For instance, low optical scattering will be of paramount importance for the imaging of extra-solar planets.

3.4 **Autonomous geophysical survey of planets**

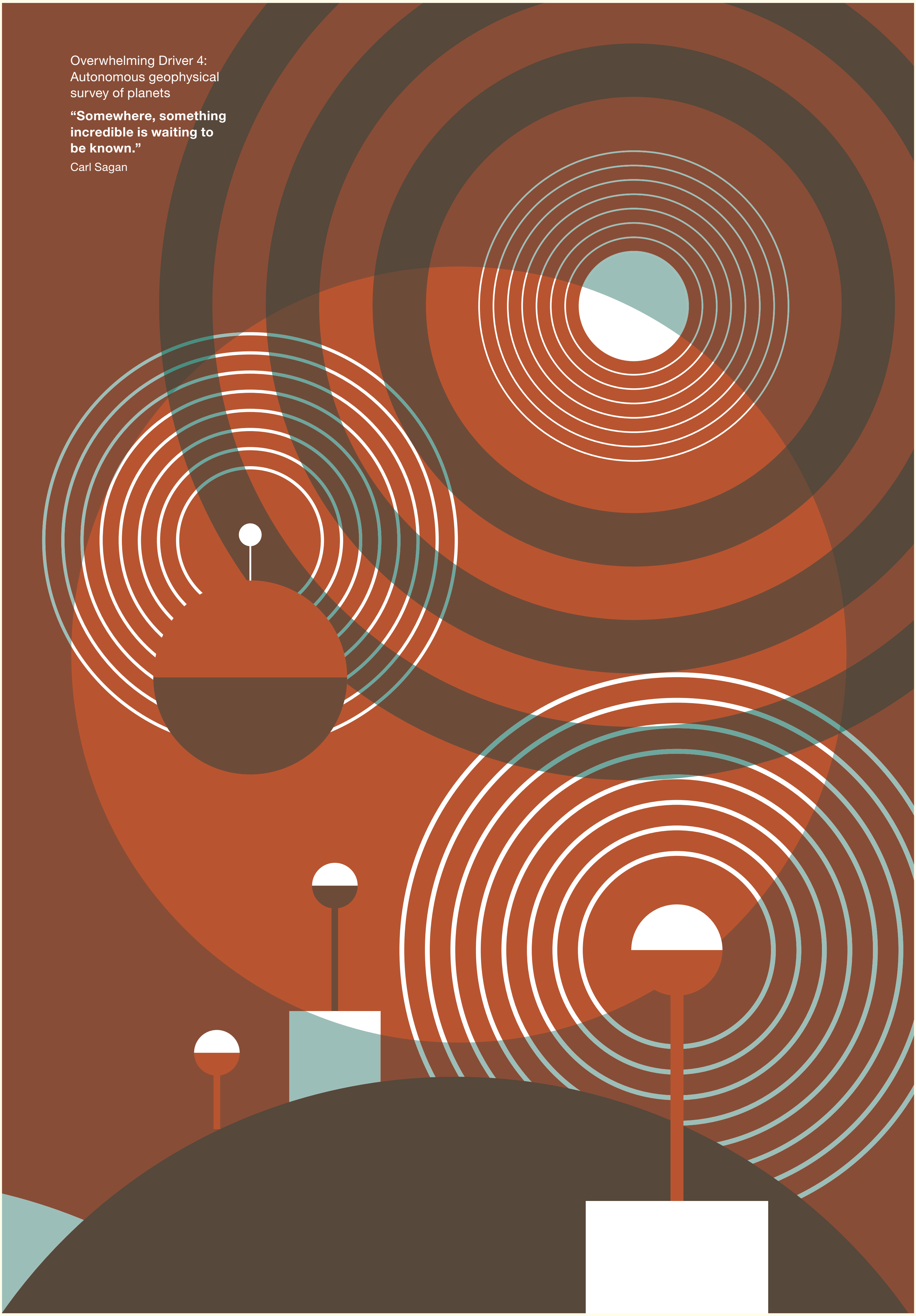
For missions to solar system bodies, the challenge is to perform as many tasks as possible in order to maximise the scientific output. Any planetary mission would carry a plethora of instruments that need to be operated in parallel. An alternative to the current mission philosophy, in which a single large complex probe is used to explore a very limited region, could be to deploy a large number of simpler but specialised probes or 'nanobots' that communicate and cooperate locally. This could allow a much larger area to be investigated than hitherto and the mission would be less prone to catastrophic failure. Probes should be complex enough to be able to perform one or more individual tasks such as drilling, sample collection or sample analysis, but not so complex as to increase the cost and risk of failure to undesired levels. This is the general problem of cost and risk management.

Mission planning cannot foresee all the eventualities of the entire mission, especially for probes that are operating in unknown environments, and telecommunications with Earth imply long delays. A high degree of local autonomy is therefore required from these missions to operate safely and efficiently at large distances. Autonomous or semi-autonomous systems are necessary for another reason. Even with a relatively large number of probes, in order to cover a significant area, the mission operations will take place over a large period of time, either in orbit or on the planetary surface. This would result in a significant number of tasks that have to be decided, planned and performed by each probe. Automation would alleviate the necessity to do everything from mission control and allow the Earth-bound specialists to concentrate on the important tasks, leaving the simple, routine tasks to the probes themselves. Similarly to the previous driver, there are two main avenues that can be explored.

The first is to minimise the mass of the probe using advanced materials and combine the instruments in such a way as to decrease their mass and/or volume. This might be achieved by sharing resources, advanced packaging and using more compact instruments that have similar performance levels. Novel antenna construction techniques would also help reduce the total weight. The second solution would be to actually split the probe in many parts that act in cooperation. Each part would be able to perform individually and collectively. Advances in sensors, Artificial Intelligence and communication methods are required for this. The final step in the process would be to replace the robots with a swarm of redundant, cooperating and specialised micro- or nano-bots, relatively cheap to fabricate *en masse*.

Table 6. Autonomous geophysical survey of planets Overwhelming Driver problematic areas and potential solutions

Problem	Potential Solution	Code
Minimise mass/ volume of instruments	Reduce the mass of instruments, in order to be able to have more instruments on board. Similar issue as OD1.1-OD1.5	OD4.1
	Novel 'packaging' techniques to increase utility per volume of instruments	OD4.2
	Compact/miniaturised instruments, similar to OD3.8 – OD3.10	OD4.3
	Miniaturisation of antennas	OD4.4
Segmented spacecraft with cooperating, autonomous parts	Artificial intelligence systems to coordinate the parts	OD4.5
	The issue of compact/miniaturised instruments, similar to OD3.8 – OD3.10, remains the same	OD3.8-OD3.10
	Advanced data transfer system development for communication between segments	OD4.6
Swarms of sensors	Mass fabrication of specialised micro/nano bots	OD4.7


Overwhelming Driver 4:
Autonomous geophysical
survey of planets
**“Somewhere, something
incredible is waiting to
be known.”**
Carl Sagan

Overwhelming Driver 5:
Enable humans to stay in space for more than two years

"I don't think the human race will survive the next thousand years, unless we spread into space."

Stephen Hawking

3.5 **Enable humans to stay in space for more than two years (Mars mission)**

Human space flight introduces many additional problems over unmanned missions. Keeping astronauts not only alive but healthy, motivated and alert for the duration of the mission will be a major challenge for any future endeavour beyond LEO. For extended missions, such as a potential trip to Mars, astronauts may have to spend periods of several years in space.

Novel ways to protect astronauts from radiation need to be developed. The medical and physiological aspects of working for such a long time in space (no gravity, isolation, radiation) are not well understood either. The life support system should also be robust and affordable, suggesting a system that recycles almost all waste products and produces food, water, oxygen and other necessities in flight. Finally, the psychological aspects of performing in isolation for long duration need to be investigated in conjunction with advanced ways of managing an isolated habitat without external contact for long intervals. For a more detailed integrated approach on these issues we refer the reader to the recently published, EC-funded, THESEUS research roadmap coordinated by the ESF.[2]

2. http://www.theseus-eu.org/

Table 7. Enable humans to stay in space for more than two years Overwhelming Driver problematic areas and potential solutions

Problem	Potential Solution	Code
Radiation damage to astronauts	Identify novel materials for shielding (similar to OD 1)	OD1.6
	Identify novel techniques for radiation shielding (similar to OD 1)	OD1.7
	New drugs for radiation treatment or radiation poisoning prevention	OD5.1
Zero-g effects on human body	Advanced countermeasure drugs, to counteract the effects of weightlessness such as muscle and bone mass reduction	OD5.2
	Simulation of gravity by technical means (i.e., centrifuges)	OD5.3
Long-duration care for astronauts' well being	Technologies to manufacture drugs and other chemicals in situ (i.e., vitamins). These drugs can either be a result of novel ways to treat the human body (RNA regulation or based on new concepts), inspired from biological processes (bio-mimetic) and nanomedicine	OD5.4
	Nano sensors for the continual monitoring of bodily functions and the environment that would not impede the crew in their duties	OD5.5
	Advanced telemedicine and telesurgery equipment for emergencies	OD5.6
	Technologies for control of bacteria, to avoid/eliminate the dangers large bacterial concentrations represent to the astronauts. This could be achieved either by using specially treated surfaces or by using mutated bacterial strains that maintain a healthy bacterial population Stress reduction Hibernation	OD5.7
Life Support Systems for long duration missions	*In situ* production of nutrition	OD5.8
	Water and air recycling. Advanced filters and catalysts based on nano-engineering could provide a significant advance in this field	OD5.9
	Technologies allowing the manufacture of parts/materials in situ (spares, modifications, servicing) through 3D printing or chemical synthesis, etc.	OD5.10

4. European Key Enabling Technologies

Key Enabling Technologies (KETs) are knowledge and capital intensive technologies associated with high research and development intensity, rapid and integrated innovation cycles, high capital expenditure and highly skilled employment. They are of systemic relevance, multidisciplinary and trans-sectorial, cutting across many technology areas with a trend towards convergence, technology integration and the potential to induce structural change. They are at the core of innovative products and they underpin the strategic European Value Chains (European Commission 2011). **A KET is, by definition, *not* a sector oriented technology.** They don't offer a complete technological solution in most cases but they enable every field to create new products and services.

The European Commission presented an industrial communication in 2002, in which it underlined the need to invest in, and advance, various Key Enabling Technologies in Europe (European Commission 2002). The seventh Framework Programme (FP7, 2007 – 2013) reflected this need, by funding research and development in the KETs. The need remains as strong today as it was a decade ago for Europe to be at the forefront of research as well as industrial production. The new framework programme, Horizon 2020 (H2020) will also focus on the KETs and their contribution to the major social challenges of our age.

The framework language makes it quite clear how important the KETs are and the drive to develop applications from basic research:

"...The first **work programmes will support research and innovation activities in all identified key enabling technologies,** notably in the fields of micro- and nanoelectronics, photonics, nanotechnologies, advanced materials, biotechnology, advanced manufacturing and processing, and other strategic drivers such as space. It will also support **cross-cutting** KET **actions,** given the potential of combinations of different KETs to create unforeseen advances and new markets. Activities will address the whole innovation chain with technology readiness levels spanning from the low end to the highest levels preceding mass production. For the higher technology readiness levels, **dedicated support will therefore be provided for larger-scale pilot lines and demonstrator projects** (including those of larger scale for technology and product validation under industrial conditions) in order to facilitate industrial take-up and commercialisation. In addition, **there will be a strong focus on the contribution of key enabling technologies to societal challenges,** including the support of KETs to all the focus areas identified..."

The key technology areas as defined by the European Commission are (European Commission 2010):

1. Nanotechnology
2. Advanced Materials
3. Photonics
4. Micro and nanoelectronics
5. Biotechnology
6. Advanced Manufacturing technologies

For the purpose of the TECHBREAK report, the definition of the KETs have changed slightly:

a) The 'Photonics' KET now specifically includes metamaterials due to the bulk of interesting developments in the field;
b) the 'Biotechnology' KET now includes medical technologies and applications, as they were more appropriate for the subject matter of the report; and

Figure 3. Key Enabling Technologies enable every field to create new products and services.
Credit: iStockphoto.

c) the 'Advanced Manufacturing technologies' KET has been merged with the 'Advanced Materials' KET.

TECHBREAK has tried to identify the most interesting technological developments to the space sector, within the European KETs. The importance of being aware of the current trends and breakthroughs in these areas is obvious, as the European KETs will receive significant funding and support and the prospects for collaboration and technology pull to ESA programmes is therefore fairly high.

4.1 Technologies that have not been included

During the TECHBREAK workshops and expert interviews, several technological areas were flagged up as interesting for space. In order to avoid repetition with other works, however, the TECHBREAK report omits several highly relevant technologies/technologies sectors. These technologies have been either covered in other reports to ESA, regarding technology development (namely the exercise recently carried out by ESA's Future Technologies Advisory Panel – FTAP), are covered in the general context of the KET technologies or there are ESA sponsored projects that deal with the relevant topics explicitly. These technologies/technological areas are:

- Artificial muscles
- Microalgae
- GaN for large wafers
- Integrated photonics for gyroscopes and sensors
- Solar concentration technologies
- Photonic sources for quantum communication, metrology and clock synchronisation
- Fibre lasers
- IR detectors
- Photon entanglement directly on chip.

4.2 Technology assessment in TECHBREAK

The assessment of the various technologies that have been encountered in TECHBREAK follows a simplified version of the well known Technology Readiness Level (TRL). The system has been adapted from the description of the TRLs, excluding the space qualification part, since the technologies are for terrestrial systems. Due to the wide range of disciplines encountered, components of the Manufacturing Readiness Level (MRL) system have been added, in order to create a system that can deal with novel materials as well as novel technologies.

The system contains four levels that indicate the technology readiness level. Level A refers to technologies or materials that are still in a theoretical/concept level, including technologies that have had 'first principle' demonstrations in the laboratory. Level B refers to technologies and applications that can be demonstrated in the laboratory. Level C refers to technologies/applications/materials that can be shown to work in a relevant or simulated

Table 8. TECHBREAK Technology Assessment System (TTAS)

TTAS	Description	TRL equivalent
Level A	**Concept**: This level includes: paper studies of a technology's basic properties, speculations on future applications of the technology, analytic studies and simulations of first principles, and laboratory studies to physically validate the analytical predictions of separate elements of the technology. This level encompasses the 'first principles' of either technology, material or technique, from pure theoretical work to 'proof of concept' experiments.	TRL 1-3
Level B	**Laboratory prototype**: Basic technological components are integrated to establish that they will work together. This is relatively 'low fidelity' compared with the eventual system. Examples include integration of *ad hoc* hardware in the laboratory. For materials, this level indicates that the material can be produced in a laboratory environment.	TRL 4
Level C	**Prototype**: Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include 'high fidelity' laboratory integration of components. Capability to produce prototype components in a production relevant environment.	TRL 5 (non-space)
Level D	**Working system**: Representative model or prototype system which is tested in a relevant environment or that is available commercially. Ability to produce a system in a production relevant environment.	TRL 6 (non-space)

Table 9. Technology development horizon description

Technology Development Horizon	Expectations
short term	breakthrough in the next 5 years
medium term	breakthrough in the next 5 - 10 years
long term	breakthrough expected in more than 10 years

Table 10. Interest in the Technology explanation of colour codes

Interest in the Technology	Explanation
niche area	niche technology area, small research community
robust interest	the community is large, healthy interest in the topic
hot topic	significant funding, very large community or interest

environment. The final level, Level D, refers to a technology that is very close to, or has achieved, commercialisation. The TECHBREAK system can be seen in Table 8.

The technologies to be described in the following sections will also be described, when possible, in terms of the expected time to the next breakthrough as well as the size of the community. The scale, once again, is kept simple and generic. The assessments are based primarily on the perception of the expert from the TECHBREAK interviews and/or research literature assessment and framework funding information where available.

5. Nanotechnology

"There is plenty of room at the bottom"
RICHARD FEYNMAN

When Richard Feynman first indicated that "there is plenty of room at the bottom" in 1959, he had already grasped the possibilities of what the mastery of the extremely small scale might offer. Although the term 'nanotechnology' was coined later,[3] it has long been evident that if humanity learned to manipulate successfully matter at the atomic scale, a new world of technology would emerge. This is what we are seeing today.

The EU definition of nanotechnology states that:

"Nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometres, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modelling, and manipulating matter at this length scale."

Classical physics breaks down at the nanoscale level. This has led to the creation of many new scientific fields that study, model and take advantage of the new physics in order to develop new capabilities and applications. Nanotechnology is therefore not a distinct scientific field but more of an *enabler* of many scientific and technological fields or the ability to interact at the nanoscale. Of all the KETs, this is perhaps the most fundamental of all. Almost all of the technologies that have been included in the TECHBREAK report involve the manipulation of matter at the nanoscale.

The world interest in nanotechnology is very large due to its immense technological potential. Accurately calculating a market figure is difficult, since there are many products that incorporate nano-enhancements but are measured as parts of other domains. Even though the market size of nanotechnology is the smallest of all KETs worldwide [table 1 of the European Commission (2011) report], the annual growth rate is the largest. Worldwide spending on research and development exceeds 10 billion € per year and it is forecasted to grow substantially for the next years as well, with a market size around 27 billion € in 2015 and a very high growth rate per year (~16%) (Cientifica Ltd 2011; European Commission 2011). As mentioned before, nanotechnology is the foundation for most of the other KETs developments as well.

This section highlights some technological developments in nanotechnology that may play a role in future space missions. Combinations of nanotechnology with other KETs, as, for example, nanomaterials, will be described in the following sections when it is appropriate.

5.1 Nanophononics

Phonons are quantised modes of vibration occurring in a rigid crystal lattice, such as the atomic lattice of a solid (Balandin, Pokatilov and Nika 2007). Nanophononics is the field of study of heat transport (expressed as vibrations of the atoms in the crystal lattice) at the nanoscale level. Nanophononics research is a more extensive subject area than thermal management though, since heat transfer underpins the science of fluctuations and noise and is therefore at the heart of information generation and transformation.

5.1.1 Nanophononics-enhanced materials

The goal of nanophononics is to understand, control and guide the acoustic or elastic oscillations in the

3. By Norio Taniguchi, a Japanese professor in the 1970s. The term referred to semiconductor processes, such as thin film deposition and ion beam milling, that took place at the nanometer scale.

Table 11. Space interesting technologies - NANOTECHNOLOGY

Technology Area	Tech Level	Development Horizon	Interest	Use	OD
Nanophononic-enhanced materials	Level A	long term	robust interest	thermal insulators, conductors, thermoelectrics	OD2.1, OD2.2
Cavity optomechanics	Level A	medium term	robust interest	cryogenics, detectors	OD3.8, OD3.9
Photothermal modulation	Level A	long term	niche area	structure monitoring	OD2.6
Nanoantennas as IR emitters	Level A	long term	robust interest	thermal management	OD2.1, OD2.2
Nanostructured surfaces	Level B	short term	hot topic	bacterial/microbial control	OD5.7
Nanoantennas for detectors/sensors	Level A	long term	robust interest	optics, detectors, spectroscopy	OD3.8, OD3.9, OD3.10
Surface plasmon resonance: biosensing	Level B	short term	hot topic	sampling, health monitoring	OD5.2, OD5.5
Surface plasmon resonance: radiation monitoring	Level A	medium term	robust interest	thermal monitoring	OD3.8
Nanoparticles for water purification	Level A	long term	robust interest	life support	OD5.9

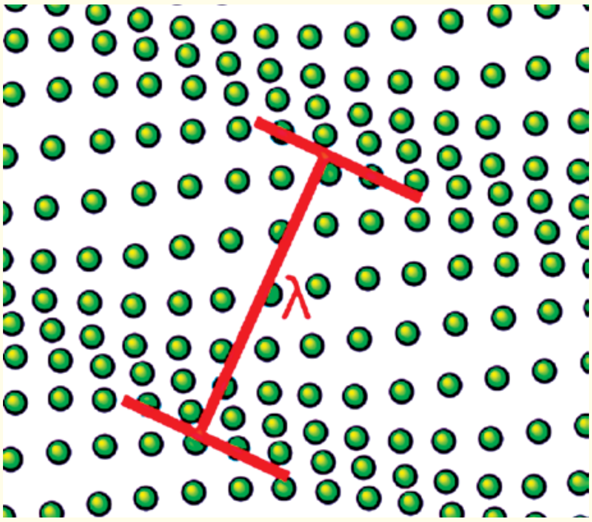


Figure 4. A phonon of wavelength λ, travelling through a crystal lattice (exaggerated scale). Credit: Florian Marquardt.

crystal lattice, which can find direct applications on sensors, on-chip devices and signal processing. Nanophononics are also extremely important in understanding energy consumption at the nanoscale level. Thermal management and dynamical control of the crystal lattice also plays a major role in packaging and integration of nano devices. Thus, nanophononics will play a major role in the future development of nanotechnology based devices and nanofabrication methods. Advanced nanophononics-enhanced material can serve as much better thermal insulators and conductors. Another potential application of nanophononics is the improvement of thermoelectric materials (NANOICT consortium 2011).

Despite the fact that heat transfer at the macro level has been an established field for centuries, the study of heat transfer at the nanoscale is a newly born discipline. The main issue and focus of the field at present is still the development of accurate simulations of the heat flow at nanoscales, developing of a robust theoretical treatment for quantum and non linear phenomena related to heat transport and, at a more administrative level, the consolidation of the fragmented research efforts at a European level. As a result, almost all of the current nanophononics work is at a theoretical level with some noted exceptions.

Technology Area	Tech Level	Development Horizon	Interest
Nanophononic-enhanced materials	Level A	long term	robust interest

5.1.2 Cavity optomechanics

The study of the interactions of phonon and photons or, as it is more widely known, 'cavity optomechanics' addresses the coupling of optical and mechanical vibrations. Light sources thus far tend to be in the IR range, with the mechanical vibrations in the MHz or GHz range, depending on the structure under study. The main goal is to use light and mechanical vibrations as mutual driving forces in order to produce transducers that can be used for extremely sensitive sensors and cryogenics, near the fundamental limits imposed by quantum mechanics. Finally, potential nanophononics applications can be in sensors and detectors that need to operate in very low temperatures. Nanophononics-enhanced detectors could manipulate the flow of phonons by nanowire structures, in order to maintain the detector at extreme low temperatures (Meystre 2013; Chan, Alegre and Safavi-Naeini 2011; NANOICT consortium 2011; Li and Zhu 2013; Arita, Mazilu and Dholakia 2013)

Technology Area	Tech Level	Development Horizon	Interest
Cavity optomechanics	Level A	medium term	robust interest

5.1.3 Photothermal modulation

A combination of thermal waves and photonics gives rise to photothermal modulation. By monitoring the backscatter radiation of a thermal pulse propagating through a medium, photothermal techniques seek to investigate the material structure and properties. This method can be useful in accurately monitoring heat flows through inhomogeneous and/or layer materials without need of physical contact with the materials (NANOICT consortium 2011). The complexity of the task is quite high and the research so far remains at theoretical level.

Technology Area	Tech Level	Development Horizon	Interest
Photothermal modulation	Level A	long term	niche area

5.1.4 Outlook

Nanophononics research in Europe, while strong, is somewhat fragmented and the research community has advised consolidation of research to common problems, mainly heat dissipation and noise in ICT related fields, as well as cross-discipline focused research on heat transport (NANOICT consortium 2011).

Entry points: Nikolay Zheludev (Optoelectronics Research Centre at Southampton University), Bruno Mourey (LETI, Optics and Photonics Department), Yves Guldner (École Normale Supérieure)

5.2 Surface plasmon resonance

Surface plasmon resonance (SPR) is the collective oscillation of electrons in a solid or liquid stimulated by incident light. The resonance condition is established when the frequency of light (photons) matches the natural frequency of surface electrons oscillating against the restoring force of positive nuclei.

SPR was first used as a label-free method of detecting molecules more than 20 years ago. In the intervening period, SPR detectors have been developed using a variety of readout methods, to detect not only the presence and concentration of chemical and biological substances, but also a variety of environmental phenomena such as radiation (electromagnetic radiation or particles), electromagnetic fields, temperature and acceleration. The sensitivity of SPR for molecular detection is many orders of magnitude better than classical methods of label-free detection such as Quartz Crystal Microbalance, for example.

SPR has been used extensively in medicine and biology for real-time analysis of molecular interactions. Current research efforts are concentrated on providing integrated bio-sensing micro-instruments and lab-on-chip sensing platforms [see, for example, Desfours et al. 2012; Escobedo 2013 and European project Plasmobio (www.plasmobio.eu)].

The effect of a single molecule on an SPR film will, however, be extremely difficult to detect. This is why a number of research groups have turned to using metal nanoparticles as plasmonic sensors. The most common method of measuring SPR shifts of single nanoparticles is to use dark-field microscopy. This technique is very sensitive but it is still difficult to measure single molecule events. A technique developed by Orrit and colleagues at Leiden University (Zijlstra, Paulo and Orrit 2012) uses a photo-thermal detecting scheme that can use much smaller nanoparticles that can detect the binding of single biomolecules through changes in the SPR absorption spectra.

A novel use of SPR in sensing has been recently demonstrated by the University of Liège. Hastanin et al. (2008) describe the concept of a bolometric micromechanical sensor for detecting far IR and THz radiation (US patent 8242446 B2), as well as another concept for droplet biosensing (Desfours et al. 2012).

Technology Area	Tech Level	Development Horizon	Interest
Surface plasmon resonance: radiation monitoring	Level A	medium term	robust interest
Surface plasmon resonance: biosensing	Level B	short term	hot topic

Entry points: Serge Habraken (Hololab, University of Liège), Menno Prins (Technical University Eindhoven/Philips)

5.3 Nanoantennas

Nanostructures that influence the flow of light with high precision can be viewed as nanoantennas. A relatively new development is to use nanostructures on surfaces in order to manipulate light in the optical and IR regime. This is a fast growing research field and many possible applications are envisaged. The recent review from Biagioni, Huang and Hecht (2012) highlights many potential applications, such as:

1. Highly-sensitive spectroscopy, where the nanoantennas provide enhanced excitation and emission of the nano-object under investigation. For example, an array of nanoantennas has been transferred to the facet of an optical fibre, used for illumination and observation of single molecule dynamics of DNA polymerase activity (Levene et al. 2003).
2. Nanoantenna-based single-photon super emitters: a theoretical model has been proposed to construct single photon sources with well-defined polarisation, optimise emission patterns and enhanced emission rates (Lounis and Orrit 2005).
3. Antenna-based photovoltaics: plasmonic enhancements have been used for a long time in IR sensors. Semiconductor based nanostructures have been proposed as a means to enhance solar cell efficiency (Cao et al. 2010).
4. Optical antenna sensors: These sensors are based on localised particle resonances. Nanoantenna based arrays coupled with a fibre facet were used to create an infrared perfect absorber (Liu et al. 2010).
5. Ultrafast and nonlinear optics with nanoantennas: it has been shown that it is possible to control coherently the localisation of hot spots of enhanced nanoantenna near fields by manipulating the temporal profile of the excitation pulse (Stockman, Faleev and Bergman 2002).
6. Efficient radiation of thermal fields, where plasmonic nanostructures are used as IR emitters (Schuller, Taubner and Brongersma 2009). This application of nanoantennas has very strong correlation with nanophononics research.

Nanoantenna technologies have been only demonstrated in the lab or are yet-to-be-realised theoretical concepts. It is a very young research field and so far the applications are mostly geared towards quantum communications and data processing with the theoretical possibility of creating plasmonic nano-circuits, once the required manufacturing techniques become available.

Technology Area	Tech Level	Development Horizon	Interest
Nanoantennas	Level A	long term	robust interest

Entry point: Brigitte Attal-Tretout (ONERA)

5.4 Nanostructured surfaces

Nanoscale structures embedded or etched on a material surface allow the material to 'acquire' new properties or enhance the already existing ones. One of the main avenues of research interest is the designing of self-cleaning surfaces that can be used as electronic displays, especially using biomimetic designs (Liu and Jiang 2012). Initially, the cost of nanostructuring was quite high due to the techniques available (Schift, Heyderman and Gobrecht 2002) but recent developments have changed this. It has been demonstrated that it is now possible not only to use scalable fabrication methods but also to implement multiple desired properties on the material.

A recent example is the fabrication of nanostructures on a glass layer, through a metallic nanomask. The nanostructures have been fabricated on the glass surface by reactive ion etching through a

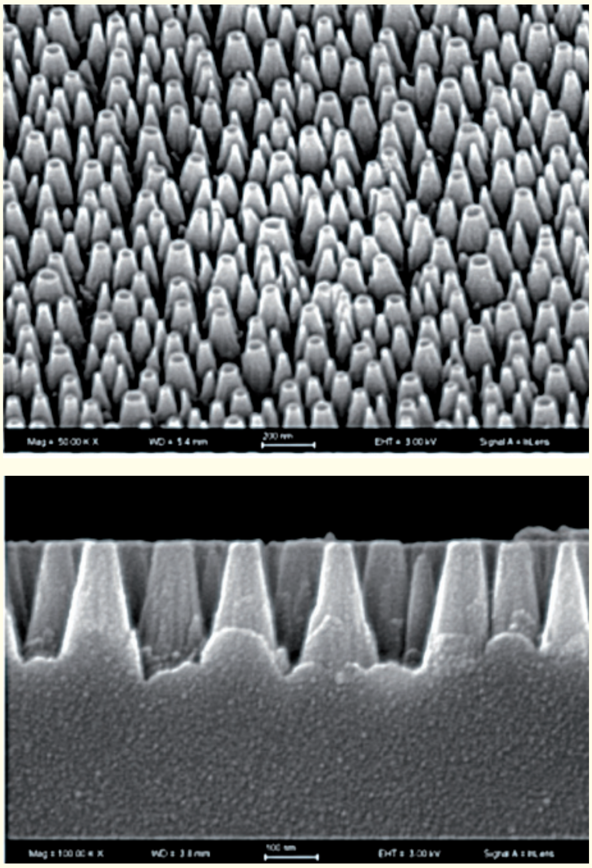


Figure 5. Nanostructured glass surface. Credit: ICFO

nanomask, which is formed by dewetting ultrathin metal films (<10 nm thickness) subjected to rapid thermal annealing (Figure 11). The developed surface nanostructuring does not require lithography, thus it can be controlled and implemented on an industrial scale (Infante et al. 2013).

This allows the production of glass surfaces that have enhanced anti-reflective behaviour, very low haze, display either hydrophobic or hydrophilic behaviour and are resistant to depositions on their surface (self-cleaning). The latter property finds applications in surfaces that are fingerprint resistant or bacterial/virus resistant. Apart from the obvious applications in consumer electronics, nanostructured surfaces can be envisaged to play a role in maintaining and controlling a low-bacteria environment in long duration manned missions.

Technology Area	Tech Level	Development Horizon	Interest
Nanostructured surfaces	Level B	short term	hot topic

Entry point: Valerio Pruneri (ICFO Barcelona)

5.5 **Nanoparticles for water purification**

Nanomaterials have been discussed as a means to purify water and make it suitable for drinking. Various nanoparticles have been used in the treatment of water (antimicrobial and antibacterial treatment) and are actually part of commercial products but, so far, an effective system that can purify *dirty* water has not been produced. There is considerable interest in substituting conventional chemical treatments of drinking water with nano-treatments, in order to eliminate harmful disinfectant products to humans as well as tackle the developing resistance of pathogens to the traditional treatments. Li et al. (2008) catalogued many available nanomaterials that are used for water treatment and the related commercial products. Some highlights include:

1. Chitosan as bioabsorber for bacteria and other biological molecules
2. Silver nanoparticles for coating of surfaces
3. TiO_2 for UV/solar water disinfection
4. ZnO for bed filters and mouthwash.

One of the challenges of nanomaterials for water treatment is to prevent the aggregation of the particles, retention and recycling of the nanoparticles from the drinking water and studies of nanoparticles' toxicity and their effects on humans. So far, most studies have utilised relatively clean or pure water. The interaction of nanoparticles and waste or impure water is still to be determined. This might have potential application in closed loop life support systems and the treatment of recycled water.

Technology Area	Tech Level	Development Horizon	Interest
Nanoparticles for water purification	Level A	long term	robust interest

Entry point: John Errington (Newcastle University, School of Chemistry)

5.6 **Conclusion**

It has to be noted that even though many new 'nanotechnology-enhanced' products and materials have been demonstrated in the lab, socioeconomic benefits from the nano revolution are yet to materialise on the scale that was predicted in the past decades for Europe. The main factors for this slow transition from the laboratory to industrial production and adoption are (NANOfutures European Technology Integrating and Innovation Platform on Nanotechnology 2012):

- The well known 'valley of death' effect, between basic research and successful commercialisation of nano-enabled products;
- Dispersion and fragmentation of efforts with private and public spending dispersed over many countries, research clusters and initiatives;
- Broad challenges that are common for high-tech sectors, namely: safety, regulation, standardisation, innovation financing and technology transfer issues;
- Inadequate focus of nano research and innovation to the social and economic Grand Challenges of our time. Such an effort would require a very broad multidisciplinary and supranational collaboration within the EU framework, something that has not materialised in the past.

Nevertheless, the efforts to bring the potential of nanotechnology to fruition are increasing and the predictions for the sector for the following decade conclude that funding will continue to increase. The World Market Size (all industries) of nano-enhanced products, services and materials is estimated to reach 3 trillion € (NANOfutures European Technology Integrating and Innovation Platform on Nanotechnology 2012) and the sector will continue

Table 12. Examples of European Research and Industrial Networks with a focus on nanotechnologies

Name	Description/Area	Type
Photonics21	Photonics21 represents photonics research & innovation priorities at European level	European Technology Platform
Nanophotonics Europe Association	An independent, not-for-profit, legal organisation to promote European science and technology in the emerging area of nanophotonics	Association
Psi-k2	Advanced Concepts in *ab-initio* Simulations of Materials	Research Network
POLATOM	Common perspectives for cold atoms, semiconductor polaritons and nanoscience	Research Network
PLASMON-BIONANOSENSE	New Approaches to Biochemical Sensing with Plasmonic Nanobiophotonics	Research Network
EPSD	Exploring the Physics of Small Devices	Research Network

to grow past 2025. Europe is amongst the leaders in research in nanotechnology and a significant effort is being made with the Horizon 2020 Framework programme to establish Europe as the market leader in nanotechnology products as well. One area where Europe is lagging behind is that of industrial production of nanomaterial and/or devices. Most of the production is being done in Asian countries and this trend will continue for the immediate future.

It is expected that the focus of development will shift from basic research to application-driven research, as is evident from the highlighting of the societal needs or challenges in the funding framework programmes. Consequently, emphasis will be given to innovation and commercialisation of products that can bring new products to the public.

5.6.1 Roadmaps on nanotechnology and nanotechnology enabled fields

1: European Roadmap for nanotechnology and optics (MONA consortium 2008)
2: Nanotechnology research directions for societal needs in 2020 (Roco, Mirkin and Hersam 2011) (USA perspective)
3: Emerging nanophotonics (PhOREMOST Network of Excellence 2008)
4: Nanophotonics foresight report (Nanophotonics Europe Association 2011)
5: Productive nanosystems, a technology roadmap (Foresight Nanotech Institute 2007)

5.6.2 Nanotechnology institutions in Europe

Regarding the funding levels for nanotechnology research and development, the USA, China and Russia (with the creation of RusNano) are outspending everyone else. Europe has a significant budget for nanotechnology although nanotechnology research funding and industry presence varies by country. The most advanced European country in nanotechnology is Germany, which hosts numerous research institutions, SMEs and large companies that deal in nanotechnologies and is a market leader in many nano-related sectors,[4] with excellent balance between basic research and industry products. It ranks third behind the USA and Japan for commercial implementation of nanotechnology related products (VDI Technologiezentrum GmbH 2011; Cientifica Ltd 2011).

Notable research institutions include the institutes of the Max-Planck-Society and the Helmholtz Association. The network of Fraunhofer institutes is focusing on the joint solution of questions regarding multifunctional layers, on the design of special nanoparticles and on the application of carbon nanotubes within the framework of the Alliance Nanotechnology. The structure of the Fraunhofer institutes and their spin off capabilities have been quite successful in the past.

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6. Advanced Materials

"To invent, you need a good imagination and a pile of junk."
THOMAS EDISON

Materials research and development is *de facto* an enabling technology, as new materials with new properties allow new applications. Every high tech sector utilises advanced materials and thus there is a widespread interest in the R&D activities of this sector.

One of the most significant, recent developments is the advancement of nanotechnology, which has boosted research into novel materials. New, exotic materials are being created in the laboratories that have the potential of offering significant enhanced performance when compared to 'normal' materials. Nanomaterials and nano-assembled materials are materials that have been artificially altered on a molecular level (nanoscale) to have novel or improved properties. Mass production of nanomaterials is a reality in certain fields (integrated electronics, sensors, photonics, biomedicine) but a wide replacement of 'normal' materials with the nanomaterials that have been demonstrated in laboratories in the past has not happened yet.

Another significant development in the field is the wide commercialisation of '3D printing' techniques for manufacturing complex designs. This trend, coupled with attempts to utilise different design principles, such as biomimetic design, has opened up a vast design space for engineers to explore. The results are quite promising, since the combination of better new materials with advanced design techniques can offer significant mass and cost savings.

The space industry has long been one of the most advanced users of materials, due to the nature of the tasks that need to be performed in the hostile environment of outer space. Especially in the field of thermal coatings and advanced structural support, the space industry has been amongst the pioneers. Nevertheless, there are some new materials that promise increased functionalities.

There are three main areas in materials R&D: a) creation of new materials; b) creation of new techniques for manufacturing materials; and c) simulations and theory, which includes software simulations, CAD designing and modelling, solid state physics theory, etc. TECHBREAK has identified topics in all three areas, which will be expanded upon in the following sections.

6.1 Advanced structural and functional materials

Research on functional and structural materials has been intensive since antiquity, since these materials underpin the industrial processes of many sectors. This encompasses the development of new materials as well as the improvement or combination of existing ones. This area includes all composite materials: from common alloys to advanced nanoengineered composite materials. These alloys are metal-metal or metal-ceramic alloys that can provide materials with hitherto unmatched properties, or combinations of properties (such as thermal, mechanical, electrical, etc.). Much of the ongoing development, as expected, is aimed at producing lighter materials and improving the efficiency of the design and manufacturing processes.

Details of the state-of the-art for many new materials and development roadmaps are to be found in the EuMaT[5] Strategic Research Agenda report (EuMaT 2012). The following section will highlight some of the expected developments within the field that can be of particular significance for space.

5. http://www.eumat.eu/

Table 13. Space interesting technologies - Advanced materials

Technology Area	Tech Level	Development Horizon	Interest	Use	OD
Advanced construction materials	varied	medium term	robust interest	new lightweight, durable materials	OD1.1, OD1.8, OD2.1, OD2.2, OD3.7
2D materials	Level A	long term	hot topic	sensors, detectors, nanomedicine, anti-bacterial treatments, solar cells	OD3.9, OD5.7, OD5.4
Topological insulators	Level A	long term	robust interest	optoelectronics, memory devices	OD3.9
Ferromagnetic and superconducting materials	Level A	long term	niche area	detectors	OD3.9
Nanoenergetic materials	Level C	medium term	niche area	efficient propulsion	OD1.8
CNTs	Level B	medium term	hot topic	lightweight materials, drug carriers	OD1.1
Boron nitride NTs : structural materials	Level A	long term	niche area	new structural material	OD1.1
Boron nitride NTs : drug delivery	Level A	long term	niche area	drug delivery	OD5.4
Boron nitride NTs : insulators	Level B	long term	robust interest	thermal protection	OD2.1
Boron nitride NTs : hydrogen storage	Level A	long term	niche area	hydrogen storage	OD2.7
Biomimetic databases	Level B	short term	robust interest	lightweight structures, robotics, sensors	OD1.2
Biomimetic design	Level B	medium term	robust interest	lightweight structures	OD1.2, OD4.2
Large scale generative production/ 3D printing	Level A	long term	hot topic	advanced fabrication techniques	OD1.2, OD1.4
3D printing of circuits	Level B	medium term	hot topic	production of robotic swarm of sensors	OD4.7
3D printing of components	Level B	short term	hot topic	repairs, spares	OD2.5
3D printing of fuel cells	Level B	medium term	robust interest	efficient batteries/fuel cells	OD1.8, OD2.8
3D printing of lenses	Level A	long term	niche area	production of robotic swarm of sensors	OD4.7
3D printing of molecules	Level A	short term	robust interest	chemical and pharmaceutical synthesis	OD5.4
Multiscale modelling	Level A	medium term	robust interest	simulations, tests	OD2.6
Active control of structures	Level A	medium term	robust interest	reduce mass, maintain stiffness, control of large mirrors	OD1.2, OD3.5

Metal Matrix Composites (MMCs)

MMCs are materials composed of a continuous metallic matrix with an embedded, reinforced phase in various amounts and forms, such as fibres, whiskers, particles, etc., and with varied composition, such as alumina, graphite, silicon carbide and others.

In the coming five years, advances are anticipated in a number of fields, such as:

- Improvement of production processes to achieve the cost reduction of aluminium and other light MMCs as well as the development of effective recycling methods
- The development of new light metal based, fibre

reinforced composites for applications in 200-300 °C range for applications such as automotive engines, electric vehicles, etc.
- The improvement of machining strategies for finishing operations of highly loaded MMCs and the application of rapid manufacturing processes of MMC components
- Improvements in the modelling of processing, microstructure and final properties for industrial applications and the creation of reliable material property databases for demanding service conditions
- Development of wear resistant MMCs, based on ferrous alloys.

Some highlights of the development roadmap for the next 10-15 years include:
- Completion of standardised material properties databases for demanding conditions
- Development of cost-effective nanostructured MMCs
- Rapid manufacturing processes for MMC component production.

Ceramic Matrix Composites (CMCs)

Similar to MMCs, CMCs consist of a ceramic matrix, with embedded ceramic fibres. These materials have been designed for extremely hot working environments and have initially found use in nuclear reactors and space re-entry vehicles. New markets for these materials now include solar power generation (solar concentrators), automobiles (braking systems), high temperature furnaces, etc. Highlights of research priorities in this field (EuMaT 2012) include:
- Development of oxidation, damage and creep resistant CMCs for turbine applications at a working temperature higher than 1400 °C
- Ceramic suspensions for development of tailored structures and compositions
- Use of non-destructive damage analysis
- Optimisation of thermal treatment
- Modelling for lifetime behaviour of CMCs
- CMC integration with other materials (joining), suitable for radiation environments
- Development of coatings for oxidation protection.

The main aims at a 10 year horizon include:
- Decrease of the cost of carbon fibres
- Development of reliable material properties databases.

Functional Graded Materials (FGMs)

FGMs are essentially metal–ceramic (or polymer) alloys that exhibit good characteristics of both worlds: higher fracture resistance and being able to withstand high temperatures. Consequently the main industrial interest in these materials is for applications in high temperature environments (aerospace, nuclear energy, etc.) The research priorities for the next five years include:
- Improved processing of FGMs
- Nano-scale graded materials
- Production of materials with hierarchical organisation for better mechanical performance
- Nanostructured coatings targeted at better oxidation resistance
- High-performance nanostructured coatings on titanium alloys.

The research priorities with a 10 year horizon include:
- Methods and protocols for graded and nanostructured coatings
- Full range modelling (atomic to macro scale)
- Fully hierarchical materials.

Given the large size of this sector, it is extremely difficult to give any accurate evaluation of the technology levels and development horizons.

Technology Area	Tech Level	Development Horizon	Interest
Advanced construction materials	Depending on material and application	medium term	robust interest

Entry point: Michal Basista (KMM-VIN)

6.2 2D materials

Two dimensional materials, as their name implies, are materials that are arranged in a single layer sheet, having a thickness of only one atom. The most famous 2D material is, undoubtedly, graphene. Graphene is a two dimensional, single layer sheet of carbon atoms arranged in a regular hexagonal pattern. It is a relatively new material (it was first isolated in the University of Manchester in 2004) and it has attracted tremendous attention and research interest, owing to its exceptional physical properties, such as high electronic conductivity, good thermal stability and excellent mechanical strength. The 2010 Nobel Prize in Physics was awarded to Andre Geim and Konstantin Novoselov at the University of Manchester for their work with graphene.

The promising properties together with the ease of processability and functionalisation make

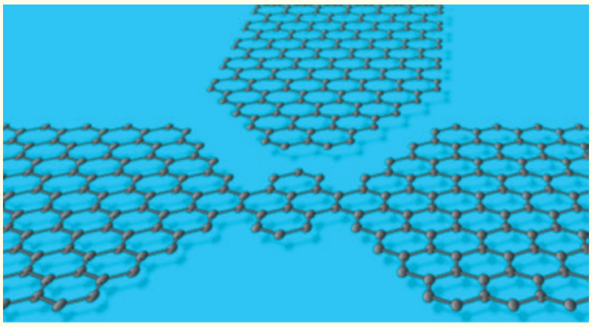


Figure 6. Artistic view of a nanometer size quantum dot, on a graphene lattice. Credit: University of Manchester.

graphene based materials ideal candidates for incorporation into a variety of functional materials. Importantly, graphene and its derivatives have been explored in a wide range of applications, such as electronic and photonic devices, clean energy and sensors. The importance of graphene for Europe is highlighted by the award of a 1 billion € grant from the European Union to the Graphene Flagship.[6]

The exceptional attention and funding that graphene research has attained makes it definitely an area to watch. The applications of graphene that are actively researched are numerous, from post-silicon electronics (Tassin et al. 2012; Schwierz 2010; K. Kim et al. 2011), sensors (Huang et al. 2011; Pumera 2011), solar cells, optics and photonics (Bonaccorso et al. 2010) to applications in the medical world such as therapy, diagnostics, antibacterial coatings, drug deliveries and many more (Pumera 2011; Mao et al. 2013).

Given the level of funding and attention this is a field that is expected to produce significant results in the future. A review of applications and a roadmap for graphene development can be found in Novoselov et al. (2012). A fabrication and production review for graphene using electrophoretic deposition can be found in Chavez-Valdez, Shaffer and Boccaccini (2013).

The attention (and funding) that graphene research has received has rekindled interest in 2D materials other than graphene. With the advancement of graphene production techniques, it became possible to produce single atom or few-atom polyhedral thick materials, all with different properties. New 2D materials have been produced, such as silicene and germanane. Butler et al. (2013) gives a review of all the new 2D materials that are now possible to produce as well as their production methods. As with graphene, these materials have numerous potential applications, such as spintronics and nanoelectronics, photonics, topological insulators (to be discussed later), phononics and energy storage.

As a result of the success of materials with 'reduced' dimensions, researchers have now started theorising on the production of 1D materials, which are essentially a long line of atoms. In theory (based on computer simulations), strands of carbon atoms can produce an extremely durable and stiff carbon atom chain, that can be stiffer than normal carbon nanotubes (Liu et al. 2013).

Technology Area	Tech Level	Development Horizon	Interest
2D materials	Level A	long term	hot topic

Entry points: Nikolay Zheludev (Optoelectronics Research Centre at Southampton University), Daniel Dolfi (Thales Research and Technology, Physics Department), Valerio Pruneri (ICFO Barcelona)

6.3 Topological insulators

Topological insulators are insulators or semiconductors that have metallic electronic states present at their boundary with other insulating materials or with vacuum (Kong and Cui 2011). Thus, the material behaves like an insulator in its interior but its surface contains conducting states. On that metallic surface, the electron spin is oriented perpendicular to its orbital momentum. The electrons that are travelling on this surface are insensitive to scattering by impurities (Moore 2010). Topological insulators are a relatively new field of study in solid state physics [a topological insulator was first proposed in Murakami, Nagaosa and Zhang (2004) and was observed in 2007 (König et al. 2007)]. The field is in its infancy but it is quickly becoming popular amongst solid state researchers.

The main (theoretical) applications for topological insulators that have been proposed so far are applications in spintronics (computer memory) and optoelectronics. The absence of backscattering from the metallic surface gives topologically insulating materials exceptional transport mobility and low power consumption and it is of potential interest to semiconductor devices. Additionally, such materials might be manufactured relatively easily with low cost techniques such as chemical vapour deposition and solvothermal synthesis. They might serve as graphene replacements for applications such as transparent conductors and wideband photodetectors (Kong and Cui 2011). Topological insulators

6. http://www.graphene-flagship.eu/GF/index.php (ESF is a partner in the Graphene Flagship consortium).

are the subject of a major research effort in Chinese universities.

Technology Area	Tech Level	Development Horizon	Interest
Topological insulators	Level A	long term	robust interest

Entry point: Yves Guldner (École Normale Supérieure)

6.4 Ferromagnetic and superconducting materials

The integration of materials on the nanoscale allows the production of integrated nanomaterials that exhibit properties that normally would be considered mutually exclusive. The term 'nanocomposites' is also used and describes a wide range of integrated materials such as atoms of one material 'trapped' within the molecular structure of another material or alternate laminates of different materials.

One such class of materials contains materials that exhibit both superconductivity and ferromagnetism and mimic the behaviour of rare materials such as $RuSr_2GdCu_2O_8$ or heavy fermion materials such as UGe_2. Superconductivity and ferromagnetism are generally considered competing or opposite phenomena. Ferromagnetism is associated with electron attraction in an anti-parallel spin orientation while superconductivity results from the alignment of spins. Ferromagnetic materials integrated with superconductors, however, allow for the *electric* command of the superconducting material instead of only thermal command.

These materials can have applications in ultrafast, superconducting, single photon detectors based on hybrid structured materials (Attanasio and Cirillo 2012). This is a relatively new area and the technology has a 10+ year horizon.

Technology Area	Tech Level	Development Horizon	Interest
Ferromagnetic and superconducting materials	Level A	long term	niche area

Entry point: Daniel Dolfi (Thales Research and Technology, Physics Department)

6.5 Nanoenergetic materials

Nanoenergetic materials are substances that have been enhanced with nanostructures for the purpose of increasing the energy output of a thermal reaction (explosives). Usually they come in the form of mixed nano-powders. These nano-explosives offer an increase in the thermal output of the reaction, have better mechanical properties and the ignition phase is often easier to control. The materials are being investigated for solid rocket propellant and pyrotechnics [see, for example, Zhang, Ang and Chou (2010) for a description of a new nanoenergetic nanowire based on Al and CuO as a new pyrotechnic device].

An alternative process to mixing nano-powders for the creation of energetic nanomaterials is reactive nanocomposite powders prepared by Arrested Reactive Milling that can be readily consolidated to achieve combined characteristics of high reactivity, low porosity and structural strength (Umbrajkar et al. 2008). Additionally, special water-repellent nano-coatings have been introduced to reactive nanomaterials to allow combustion in environments where this was not possible before, such as underwater (Collins et al. 2013).

Most of the research is based in the USA and Canada. These materials will offer improved solid propergols and explosives.

Technology Area	Tech Level	Development Horizon	Interest
Nanoenergetic materials	Level C	medium term	niche area

Entry point: Brigitte Attal-Tretout (ONERA)

6.6 Carbon nanotubes (CNT)

Carbon nanotubes have been often portrayed as materials that will transform many industrial and scientific fields. Some of the unique properties of CNTs are: having a very high known Young's modulus (>1 terapascal); having the ability to conduct high electrical current densities; being extremely resistant to hot acids; being an excellent carrier for chemical and biological marker molecules; having the ability to adsorb large quantities of hydrogen; etc.

As with many new materials, the range of applications where this material would, today, provide a cost-effective solution is limited and will take time to develop. Nevertheless, such materials have great potential for the space industry, combining 'the mass of aluminium and the strength of steel'.

Several national governments in Europe have formed collaborations to develop and commercialise CNT technology. The German government, for example, has established a CNT innovation alliance, inno.CNT,[7] which comprises about 100 German institutions from academia and industry (including Bayermaterials) that are developing CNT technology or wish to produce products based on it. Inno.CNT is part of the German government's high-tech strategy and is sponsored by the Federal Ministry of Education and Research with the purpose of "mobilising additional innovative forces in a technological field which is crucial to the competitiveness and growth of German industry". But apart from a few niche products, it will take 5 – 10 years before this technology becomes more widely understood and available to manufacturers. Although CNT technology is listed in this section under 'advanced materials', it has a much broader range of applicability to the Overwhelming Drivers as mentioned elsewhere in the TECHBREAK report.

Technology Area	Tech Level	Development Horizon	Interest
CNTs	Level B	medium term	hot topic

Entry points: Michal Basista (KMM-VIN), Daniel Dolfi (Thales Research and Technology, Physics Department)

6.7 **Boron nitride nanotubes**

Similarly to CNTs, boron nitride nanotubes (BNNTs) can also serve for the creation of multifunctional structural composites. Boron nitride (BN) consists of equal numbers of boron and nitrogen atoms. Boron nitride is not found in nature and is therefore produced synthetically from boric acid or boron trioxide. BNNTs are electrical insulators with a wide bandgap of ~5.5 eV. BNNTs are more thermally and chemically stable than carbon nanotubes. BNNTs are the strongest lightweight nanomaterials on Earth, with a Young's modulus of 1.2 TPa (Wang, Lee and Yap 2010).

Despite their extraordinary property, research activities on CNTs are much more popular than that of BNNTs. Among the major reasons for this situation is that the syntheses of BNNTs are much tougher than that of CNTs, requiring excessively high growth temperatures (>1300°C), involving special instrumentation or dangerous chemicals. This has limited the availability of BNNT samples for experimental study of their properties and applications.

BNNTs can serve for reinforcement of polymeric composites and ceramics, in order to reduce mass while maintaining stiffness (cf. OD1, section 3.1). They are preferable to CNTs for hydrogen storage because ionic B–N bonds induce a dipole moment between hydrogen and the nanotubes for stronger binding. BNNTs have a higher chemical stability than CNTs at elevated temperatures. Results show that they can survive in excess of 1000 °C and they have been used in ceramics for years (Wang et al. 2010).

BNNTs may also have potential applications in the medical domain, both as nanocarriers for drug delivery and topical treatment of diseases, as well as nanotransducers for biomedical sensors (Ciofani et al. 2013). The field is still in its infancy though and so far only studies on the reaction of BNNTs with living cells have been performed.

Entry point: Brigitte Attal-Tretout (ONERA)

Some other potential European contacts are: Institut Lumière Matière in Lyon (CNRS / Université Claude Bernard Lyon), Institut Néel (CNRS) as indicated in Siria et al. (2013). Another potential contact is the Centre for Micro-BioRobotics at SSSA (Istituto Italiano di Tecnologia).

Technology Area	Tech Level	Development Horizon	Interest
Boron nitride NTs: insulators	Level B	long term	robust interest
Boron nitride NTs: structural materials	Level A	long term	niche area
Boron nitride NTs: hydrogen storage	Level A	long term	niche area
Boron nitride NTs: drug delivery	Level A	long term	niche area

6.8 **Transparent electrodes**

Transparent electrodes are an essential component of touch screens, LCDs, OLEDs and solar cells. Naturally, the demand for transparent electrodes is extremely high, as these technologies are extensively used in consumer electronics. Thus far, the most popular material for these electrodes was indium tin oxide (ITO). Unfortunately, ITO is in scarce supply and due to its ceramic nature, it is easily damaged (Hecht, Hu and Irvin 2011).

7. www.inno-cnt.de

Figure 7. Ultra Thin Metal Film, used for projecting the view from the rear of the car (heads-up display function). Credit: ICFO

The most common transparent electrodes apart from ITO are conducting polymers that are widely used for mobile phones, photovoltaics and other devices. Polymer electrodes offer many advantages, particularly their low cost. Unfortunately, low efficiency and low durability has not allowed polymer electrodes to be the replacement of ITO yet.

There are several other candidates for replacement of ITO as the transparent electrode of choice: CNTs, graphene and ultrathin transparent metal grids and nanowires. So far, no specific technology has demonstrated its superiority and research continues on refining the production techniques and demonstrating new capabilities [see, for example, Pruneri (2013); Ghosh et al. (2013); Chen et al. (2012)].

This technology has many applications in electronics and particularly in solar cells and touch screens. There is extensive research on this field in Europe and world wide due to its commercial applications.

Technology Area	Tech Level	Development Horizon	Interest
Transparent electrodes	Level B	short term	hot topic

Entry point: Valerio Pruneri (ICFO Barcelona) and Herman Schoo (TNO-Holst Centre, Eindhoven)

6.9 Biomimetic design

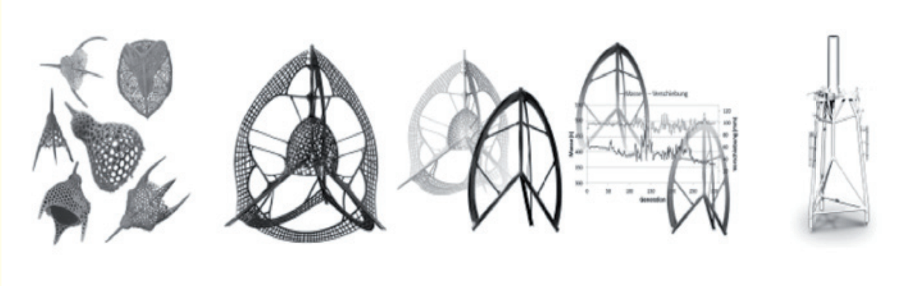
Reducing mass is central to space endeavours. For non-active structures, there are two possible paths; either replace the materials with new, lightweight materials, or use a different design, that can maintain the expected mechanical loads with less structure, thus less mass. Traditionally, lightweight design is closely tied to the abilities and limitations of modern CAD (Computer-Aided Design) programmes and manufacturing methods. Biomimetic design, on the other hand, is a design that is based on the design of highly evolved natural organisms.

Biomimetics is the field of study of the functionality of biological systems and the way those systems have solved various problems in the real world, with the aim of transferring or applying those solutions to an engineering problem. The adaptation of the biological solution can come in two forms, either by directly adopting the solution [i.e., adhesion tapes based on the way geckos 'stick' to vertical walls (Rodriguez et al. 2013)] or by exploiting genetic algorithms and optimisation based on natural selection methods to optimise the design of certain structures or a combination of the two methods (Lee and Szema 2005; Marco et al. 2013). Up to now, biomimetic design concepts have had little more than a curiosity value largely because of the difficulty of translating a biological design into a manufacturable engineering design.

Biological structures are more irregular than conventional engineering designs. A honeycomb structure, which is easily produced by cut-and-paste techniques, can add stiffness to a structure but also often leads to vibrational resonance peaks due to the honeycomb's regular spatial frequency. Biological structures, in contrast, have a more fractal design which, while adding stiffness, also has fewer resonances and better damping characteristics. Good self-damping is an important attribute for structures in space.

The Alfred Wegener Institute (AWI) in Bremerhaven has addressed this problem by developing a novel way of taking a biological design and 'evolving' it into an engineering design than can be manufactured using conventional methods. This process is known as ELiSE – Evolutional Light Structure Engineering.

AWI's starting point is a catalogue of over 90,000 different forms of plankton. Although microscopic, these exoskeletal organisms have all evolved to resist large physical environmental loads with minimum structural mass. The design process consists firstly of screening the database to find the plankton forms that most closely fit the functionality of the desired component. These are then analysed using CAE (Computer-Aided Engineering) techniques to examine the load cases. The selected biological design is then simplified and optimised ('evolved') to reach a final engineering design. This process has already been applied to a number of engineering projects, including the supporting structure of an offshore wind turbine (48% weight saving without change of material), car wheel hubs



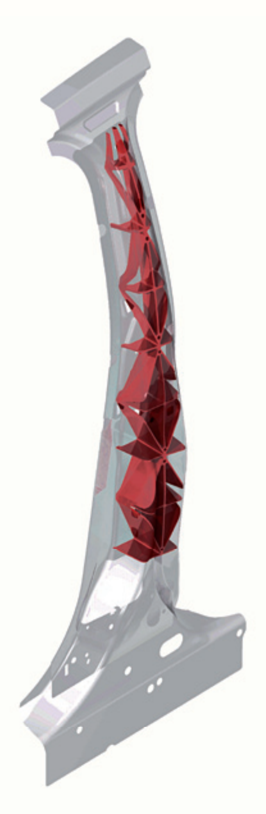


Figure 8. EliSE procedure (from left to right): i) Planktonic organisms are screened for structures that have similar functions to the given problem, ii) The load cases of the given problem are analysed, iii) the construction methods and archetypes are abstracted, iv) the model is elaborated and further optimised and v) the best solution is referenced to the mechanical problem at hand (in this case, the base of an off-shore platform). Credit: AWI

Figure 9. Bionic B-Pillar for offshore platform, designed using the ELiSE procedure for Stadco Saarlouis ltd. & Co. Credit: AWI.

(20% weight saving), and an orthopaedic cast (50% weight saving). An outline of the method can be seen in Maier et al. (2013).

As the biomimetics field is growing, the amount of information catalogued regarding natural designs and organisms grows. Combined with the gains in computational power, it will allow the creation of databases that can be used to optimise and tailor solutions to specific problems. New fabrication methods are expected to allow increased structural complexity of lightweight structures, including multimaterial solutions and differentiated use of tensile and compressive structural components.

A common characteristic of biological design and spacecraft design is the growth of protected spaces within a hostile environment. This is an issue of paramount importance for certain microorganisms as well as manned spacecraft. Thus, biomimetic solutions could be adopted for habitat design (Kuksenok and Balazs 2013). Additionally, robotics often mimic biological systems for inspiration, either for locomotion, sensing techniques or communication architectures (Chu et al. 2012; Martinez, Rochel and Hugues 2006; Delcomyn 2004; Madden 2007).

The expectations of biomimetic design include (long term horizon):

- Increasingly generic or mathematic generation of 3D-lightweight structures
- The more rapid assessment of structure performance (FEA – FEM plus computer power)
- Effective generative production methods that are much faster than current laser sintering, stereolithography, etc.
- Energy-saving production methods, e.g., cold-casting of highly resilient materials (in analogy to silica precipitation of diatoms) that are more efficient than production methods such as injection moulding
- Adaptation from mass produced, 'one-size-fits-all' products to products adapted to the specific individual technical solution.

Biological designs are invariably more complex than conventional engineering designs. There are manufacturing limitations that severely restrict the design of the parts to be produced. With recent advances in 3D printing techniques, this gap seems to be closing. The following section deals with 3D printing as a production and manufacturing technology.

Technology Area	Tech Level	Development Horizon	Interest
Biomimetic databases	Level B	short term	robust interest
Biomimetic design	Level B	medium term	robust interest

Entry point: Christian Hamm (Alfred Wegener Institute)

6.10 **3D printing**

3D printing forms a natural complement to biomimetic design. Although the components produced by 3D printing are currently rather small, this is a technology that has enormous future potential and is progressing quite fast. This was recognised by both ESA and NASA who have launched their own development programmes to promote the technology (e.g., ESA's AMAZE project and NASA's ADMMS project).

The recent advancements in additive manufacturing process, the novelty factor (even though the technique has been around for decades) and the futuristic promises of creating anything with a push of a button, has captured the imagination of the public. 3D printing is now available to private hobbyists who can afford ~2,000 € for a home printer (Fab@home, 2 syringe system), with 3D printer CAD files freely available for download from the internet.

Additive manufacturing has also attracted significant press lately and as a result, especially in the U.S., there has been an increase of venture capital available to start-ups that promise new and novel products as well as major companies that trade publicly in the stock market (STRATASYS and 3D systems Corp). Europe has led the research in 3D printing and some of the most advanced techniques can be found in European companies and universities (Eklund et al. 2007; Beaman et al. 2004). Nevertheless, the 3D printing consumer movement is stronger in the USA.

Industry is nevertheless still facing some issues today that inhibit the wide adoption of 3D printing as the main manufacturing method:

1. A very limited number of input materials (mainly plastics and some metals, with the rare exception of liquids in certain cases and biological cells for medical applications).
2. High cost of production, since the input materials are quite expensive. There is no scaling law yet for 3D printing that reduces the cost of production according to the number of objects. The price per object remains the same, regardless if you print one object or one million.
3. Time intensive production. It can take hours or even days to print one object.
4. Inability to use multi-material manufacturing, which makes it impossible to produce anything more than a one-piece object.
5. Modern printers cannot consistently produce the same final product. There are significant variations in quality and geometry of identical products produced with different machines.
6. 3D printers lack hardware reliability.
7. A large number of 3D printers require skilled operators in order to function well. Furthermore, the current software capabilities for designing and calculating properties and stresses of complex systems are not as robust as they should be. Today, only linear elasticity is taken into account when performing topology optimisation in commercial software. Given the complex geometrical shapes, a simple user will not be able to design and calculate the properties of an object correctly, which is not an issue for R&D usually but plays a significant role in the commercial proliferation of 3D printers.
8. Most vendors have a closed architecture that prohibits researchers changing the process to suit their needs.
9. Availability of CAD models is an issue; it is not trivial to scan an item in such a way as to make a 3D printer understand its shape and geometry.
10. Usability of models is also limited, especially since the sintering process produces objects that are weaker than traditional methods.

The discussion regarding massive adoption of 3D printing techniques in space is, thus far, in the conceptual scenario phase. 3D printing is considered as a great technique to save on fuel and costs by utilisation of *in situ* materials on the Moon and asteroids to build new spacecraft for solar system exploration and exploitation but this remains very high level speculation (Metzger et al. 2013). Nevertheless it must be noted that aerospace companies are actively qualifying various parts for flight (Wohlers 2012).

The last decade has seen the rise of metal source materials as feed in 3D printing. European companies are highly advanced in the field. Most systems are based on powder bed fusion technology and four companies offer systems that use directed energy deposition technology. Printers for high-temperature materials are only designed in Europe (Leu, Bourell and Rosen 2009). Examples of powder bed fusion systems are the direct metal laser sintering (DMLS) process from EOS and the selective laser melting (SLM) technique from Renishaw. Laser engineered net shaping (LENS) from Optomec is an example of directed energy deposition (Wohlers 2012).

At present, 3D printed metal processes cannot compete with traditional machining and casting processes in volume, cost or quality of finish. There are special cases where the 3D method is preferred such as the production of low volume, complex products with internal channels or cavities. One point where 3D printing has a definitive advantage over traditional methods is waste. For metal printers, all of the unused metal powder can be recycled,[8] whereas polymer printers have a 30%-40% waste ratio.

Many types of metals are available on metal printing systems. Among the most popular for medical and aerospace applications is the titanium alloy Ti-6Al-4V. Other metals used are cobalt–chrome, stainless steels, tool steels, aluminium such as $AlSi_{10}Mg$ and 6061T6, jewellery and dental gold alloys, and nickel-based super-alloys such as Inconel 625 and 718. Aerospace-grade aluminium and other metals are actively in development (Wohlers 2012).

8. This is a good thing, since 30-80% of powder (depending on the shape) is not able to be used in the process.

Regarding polymer printing, the industry is experimenting with novel materials including self-healing polymers, stereolithography (SLA) polymer resins with improved part time stability after fabrication, development of affordable high-temperature polymers, integrated optics gradient materials (diffraction or dispersion filters, etc.), *in situ* sensors, self-assembled single crystals (e.g., aluminium nitride), continuous filament composites, and point-to-point control of materials properties and composition (Leu et al. 2009).

Cutting-edge development includes (Leontiou 2011):

- Laser assisted production of very thin tube structures to serve as blood vessels
- A food printer that works with softer foods, which can be poured into a print head and then pumped out via syringe to form whatever intricate design the digital blueprint calls for, developed by students at Cornell University in collaboration with New York's French Culinary Institute
- The SULSA, the first entirely 3D printed aerial drone. It has a wingspan of two meters and can travel at speeds of up to 100 miles per hour
- Clothes, mostly from a nylon derived material
- The first self-replicating (still needs assembly) machine, in the form of the 3D printer RepRap, which is made from plastic components that can be printed by the printer itself.[9]

3D printing of optical lenses has been discussed as an extremely attractive ability to have, although the accuracy to print optical lenses or mirrors does not exist yet. There are some efforts to produce a working lens (Yanaka, Kira and Kasuga 2012) but with limited applications. It is doubtful that it would be possible to manufacture a lens or a mirror for a telescope in this way but the technology could perhaps be utilised for the *in situ* production of many small optical parts for a swarm of sensors in the future.

One interesting development is the demonstration of production of 3D printed electronic circuits by Sandia National Laboratories and the University of Texas. The printed circuits function like traditional circuits but can be printed on the contours of the product. That development could potentially lead to volume savings, as the circuit itself can be part of the structure and will not need additional units (Leu et al. 2009).

Another potential application of 3D printing is the production of very small fuel cells or batteries. 3D printing can produce the often complex geometries that are required for ultra-efficient, small scale power sources. A recent example was the production of lithium-ion micro-batteries the size of a grain of sand, by a team from Harvard University and the University of Illinois at Urbana-Champaign.[10]

3D printing found its way also in the domain of reactionware for chemical synthesis and analysis, via a novel approach, which creates a cost-effective, automated and reconfigurable chemical discovery platform that makes techniques from chemical engineering accessible to typical synthetic laboratories (Symes et al. 2012) or by the production of miniaturised fluidic 'reactionware' devices for chemical syntheses in just a few hours, using inexpensive materials producing reliable and robust reactors (Kitson et al. 2012).

It is expected that the growing demand for smart materials will provide a boost for printing techniques that combine polymer based systems with printed metal traces (which will serve as conductors). So far, it is almost impossible to pause the printing procedure to insert any other devices, without the end product being damaged.

Finally, the micro and nano world will probably benefit significantly from 3D printing, especially if new materials are made available. Extreme precision sketching has been around for years and the techniques are drastically improving. Recently, the German company Nanoscribe produced structures with feature sizes ranging down to just 100 nanometres, demonstrating a 100 fold decrease in printing time.[11] 3D printing is an enabling technology that may benefit many other areas, while it is still difficult to capture its impact.

As the functionalities of 3D printing continue evolving, 4D printing has made an appearance on the horizon.[12,13] Similar to 3D printing, but having the extra feature of combining various materials that in contact with light, temperature, water or other external forces will change their initial shapes and properties, adding the time element to a design. Once the material is printed, due to the influence of the factors mentioned above, it will undergo a transformation of its shape to conform to the desired outcome.

9. http://reprap.org/wiki/Main_Page

10. http://www.seas.harvard.edu/news/2013/06/printing-tiny-batteries

11. http://www.futuretimeline.net/blog/2013/02/10.htm#.UchZIor7Ens

12. http://www.rdmag.com/news/2013/10/grant-opens-new-dimension-printing-4-d

13. http://3dprintingindustry.com/2013/02/27/are-you-ready-for-this-4d-printing-is-on-the-way/

Technology Area	Tech Level	Development Horizon	Interest
Large scale generative production/ 3D printing	Level A	long term	hot topic
3D printing of components	Level B	short term	hot topic
3D printing of circuits	Level B	medium term	hot topic
3D printing of lenses	Level A	long term	niche area
3D printing of molecules	Level A	short term	robust interest
3D printing of fuel cells	Level B	medium term	robust interest

Entry points: Christian Hamm (Alfred Wegener Institute), Lee Cronin (Glasgow University)

6.11 Active structures

Making very stiff structures has traditionally implied either increasing the mass, using materials with increased Young's modulus, or both. An alternative approach is to use adaptive structures that achieve 'stiffness' by actively controlling the shape of the structure and correcting an error in shape or form by using a mechanism elsewhere in the system. An additional advantage of fast active control of structures is the ability to actively damp structural vibrations.

In a space environment, adding additional mechanisms also increases the risk of failure and hence is not always advantageous at a system level. Active structure correction mechanisms therefore need to be reliable, have low power consumption, be fail-safe and allow redundancy.

Potential solutions that meet all these requirements are piezoelectric and electrostrictive devices. The main difference between the two is that electrostrictive devices only expand when a voltage is applied, whereas piezo devices expand or contract according to the direction of the field applied. Piezo devices show a higher hysteresis and are therefore more suitable for closed-loop applications. Both types of devices are used extensively for fine alignment applications or adaptive mirror actuators and several groups have experimented with these, for example, for active control of mirrors (Dai et al. 2012; Gonté et al. 2009; Bastaits et al. 2009).

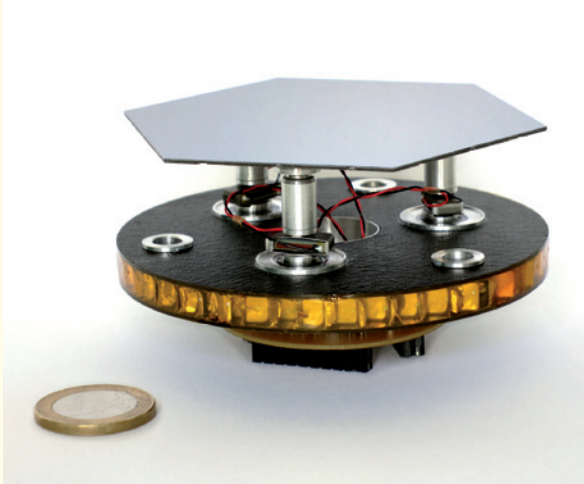


Figure 11. Si-PZT Bimorph segment mirror prototype for Adaptive Optics on its isostatic support mounted in the sandwich CFRP support plate. Credit: ESA-GSTP-BIALOM

An interesting variant for active control of structures are piezo fibres, which are typically sandwiched between two flexible electrodes that can be bonded to the structure. Such piezo-fibre composites are convenient to manufacture but suffer from the drawback that the epoxy used to attach and encapsulate the piezo fibres has a much lower electrical permittivity than the PZT fibres. Thus, even with a very thin epoxy layer, most of the applied electric field is lost in the epoxy. A much higher applied voltage is therefore necessary to achieve the required stress which, in a space environment, is an obvious disadvantage. Square or rectangular extruded fibres with the electrodes directly deposited on opposite sides of the fibre would overcome this problem but would be significantly more difficult to manufacture.

There are essentially two main approaches that have been developed for piezo fibres: active fibre composites (AFC) and coaxial fibres with a conducting core and external conduction sheath. The materials used are either PZT (ceramic) or PDVF (polymer) and are commonly produced either by

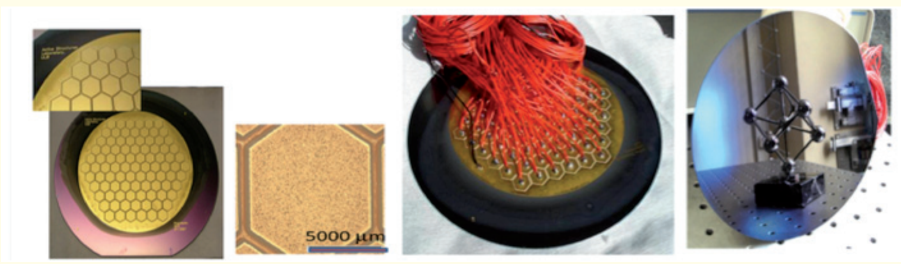


Figure 10. A Bimorph Mirror prototype. From left to right: Actuator PZT film, a gold electrode of an individual actuator on scale, the control and the wires and the reflecting surface. Credit: Active Structures Laboratory, University of Liège

extrusion (making them similar in cost to circular fibres) or by spinning. Both methods are used in actuators and sensors. Piezo fibres are currently used for active control in the avionics industry, vibration damping in machines and wind turbines, stress and vibration monitoring, etc. (Williams et al. 2002; Bowen et al. 2006; Brunner et al. 2005; Melnykowycz and Brunner 2011). The original work on AFC was funded by DARPA in 1997.

There seems to be a growing interest in active control in several large national research laboratories such as TNO in the Netherlands, Fraunhofer institutes in Germany, VTT in Finland. Although technological development would be necessary, there is great potential for solving issues that will arise when constructing a 30m+ space telescope, for example.

Technology Area	Tech Level	Development Horizon	Interest
Active control of structures	Level A	medium term	robust interest

Entry points: André Preumont (Université Libre de Bruxelles), Serge Habraken (Applied Research Centre, University of Liege), Chris Bowen (Mechanical Engineering Dept., University of Bath), Andreas J. Brunner (Swiss Federal Laboratories for Material Testing & Research), Bernhard Brunner (Fraunhofer ISC), Mikael Rigdahl (Materials and Manufacturing Technology Dept., Chalmers University)

6.12 Multiscale modelling

The advances in materials and nanotechnology have provided scientists and engineers with new metals, ceramics and composite materials which have better or more useful characteristics than the normal, non-engineered materials. Alongside the increase in functionality, an increase in complexity is pushing the limits of what can be simulated with traditional software methods. The boundary conditions of the simulations have also changed, with the need to simulate both the nanoscale as well as the macroscale. For demanding operational environments like space, there is also the need to simulate long exposures in time and study the effects on materials in long timescales.

Multiscale modelling entails the application of modelling techniques at two or more different length and timescales, which are often, but not always, dissimilar in their theoretical character due to the change in scale (Elliott 2011). This approach has gained attraction in the materials community due to the aforementioned demands from new engineered materials, as well as the increase of the computational power available to perform such simulations. One of the goals is to eventually link traditional Finite Element Analysis of structures with the microscopic level simulations. Applications of the numerous techniques that have emerged can be (Elliott 2011):

1. Studies of the diffusion and radiation damage in metals, particularly nuclear power plants
2. Studies of the properties of nanometals and alloys
3. Studies of large fracture behaviour in ceramics
4. Novel fabrication methods using biomimetic algorithms for nanostructures.

Successful software tools have already been developed that can perform multiscale modelling for nanomaterials, although a true combination between the nano level and the macro level for a complicated structure, such as a spacecraft, has not been done yet.

When KMM-VIN was approached, one of their comments was that despite being involved in over 50 research groups' collaborations, they miss strategic partners in the 'Materials for Transport' work group, which includes also space transport. Strategic partners, often from industry or directly linked to industry, suggest research problems for KMM-VIN consortia as a part of their joint research programmes of the work groups and initiate multi-partner research projects involving materials processing, characterisation and modelling groups from different European research centres. Strategic partners are engaged with KMM-VIN in problem formulation and subsequent involvement in some research tasks.

There is significant interest in this field from all industrial sectors. Working Group 1 of the European Technology Platform for advanced engineering materials and technologies (EuMaT 2012) deals with this topic.

Technology Area	Tech Level	Development Horizon	Interest
Multiscale modelling	Level A	medium term	robust interest

Entry point: Christian Hamm (Alfred Wegener Institute)

6.13 Conclusions

There is no doubt that advanced materials will play a significant role in Europe in the future. Today, extraction, processing and manufacturing are estimated to represent around 20% of EU's GDP. The emerging technologies are also poised to drive European growth and employment in the future and the need for advanced materials is only going to increase (EuMaT 2012).

Advanced Materials platforms and programmes in Europe

The EuMat European technology platform involves all elements of the full life cycle of industrial products, from design, production, optimisation and testing. The platform is comprised of seven working groups that focus on:

1. Modelling and multiscale
2. Materials for energy
3. Nanomaterials and nanostructured materials for functional and multifunctional applications
4. Knowledge-based structural and functional materials
5. Lifecycle, impacts and risks
6. Materials for Information and communication technologies
7. Biomaterials.

One of the contributing organisations to this study is the European Virtual Institute on Knowledge-based Multifunctional Materials (KMM-VIN). It is a collaboration of almost 70 members and association members from academia and industry in Europe that carry out research and development on a broad range of advanced structural materials. In particular, this includes the analysis and numerical modelling of the effective properties of materials, damage and fracture processes in metal-matrix, ceramic-matrix and infiltrated composites using micro computed Tomography (micro-CT) imaging of the microstructure of real materials. KMM-VIN can also provide coordination, consultancy and educational services from its members.

The 'Graphene and Nanotubes: science and applications' (GNT) group is a national research group (GDR 3217) and an international coordination network (GDRI) cross-linking research on nanotubes and graphene. The group brings together French, European and Canadian partners who have played a major role in the activities of the previous GDR, as well as scientists of international reputation working on graphene.

Finally, as mentioned before, the European Flagship programme GRAPHENE is a 10 year, 1 billion € funded initiative that aims to take graphene and related layered materials from the academic laboratories to society and revolutionise industries in Europe, while fostering growth. The consortium is comprised of 61 academic partners, 14 industrial partners and spans 17 EU countries. The first call for proposals closed on 5 February 2014.[14]

GRAPHENE FLAGSHIP

Figure 12. The GRAPHENE flagship, The Graphene Flagship coordinates 76 academic and industrial research groups in 17 European countries (www.graphene-flagship.eu).

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7.
Photonics and Metamaterials Research

"Never fire a laser at a mirror. "
LARRY NIVEN

Photonics is one of the most rapidly growing industries, not only in market terms but also in applications. Lasers and optical fibres have transformed the Information and Communication industry and are the back bone of the modern 'Information Age'. Current estimates give a market size of 300 billion € worldwide for photonics (not counting sectors that are directly impacted from photonics development). Europe has a significant share of the world market, ranging from 20% to 45% depending on the sector and applications (Photonics21 2011). As mentioned before, the market growth of photonics is significant, more that 10% per annum and it is expected to grow even further.

The ability to produce and manipulate light in novel ways has several technological applications. The most important one, due to its importance for the future, is that photonic circuits offer a way to go 'Beyond Moore', providing an alternative to modern electronics that is not bound by the limitations of silicon. Even though pure photonic circuits have not yet been produced, photonic/electronic hybrids are actively developed and the industrial race to be the first to successfully commercialise the first photonic circuit is well underway.

Another important breakthrough, made possible through the advancement of nano techniques that allow the direct structuring of materials, is the field of metamaterials (MMs), a new 'breed' of materials that acquire their properties from their artificially designed structure and not the natural properties of the material itself. Their structure consists of nanostructured building blocks, smaller than the length scale of the external stimulus, designed in such a way as to exhibit distinct responses to light and heat flows that are not attainable with naturally available materials.

The combination of increased ability to manipulate the interaction of light with materials and the substitution of the electron with the photon as information carrier is one of the most powerful technological capabilities in the modern world. The field is experiencing rapid growth and, with the expected penetration of nanomechanics into nanophotonics and nanoelectronics, it is expected that significant metamaterial based game changing technologies will appear, influencing development in photonics and electronics, as well as sensors.

Integrated photonics is full of potential, in particular towards integration of photonics and electronics in space. More than having a compact instrument, it is the integration itself which is important with gains in many areas (cost, size, radiation hardening). This area is one of the most intensely competitive areas of development and research, as it is projected to offer capabilities beyond standard CMOS technologies. IBM was the first to demonstrate a commercially viable fully integrated optical and electronic chip that can be manufactured with a standard semiconductor process in 2012 (Assefa et al. 2012). In Europe, the photonics research cluster on the Saclay plateau is poised to be the largest concentration of public researchers in photonics.

To date, photonics has been used for light transport, filtering, noise suppression, interferometry, and making artificial guide stars. But there are many photonic functions yet to be explored. Most of them will doubtless be restricted to optical and

Table 14. Space interesting technologies in the area of photonics and metamaterials

Technology Area	Tech Level	Development Horizon	Interest	Use	OD
Photonics on chip	Level C	short term	hot topic	radiation protection, communications	OD1.4, OD1.6, OD3.8, OD3.9, OD4.3, OD4.6
Photonic crystal fibres	Level C	medium term	robust interest	sensors, radiation resilience	OD1.3, OD1.6, OD3.9
Aerogel photonic component packaging	Level C	medium term	robust interest	thermal protection	OD2.1
Sapphire PCFs	Level C	long term	robust interest	thermal management	OD2.1
Microresonators	Level A	medium term	robust interest	spectroscopy	OD3.9
Nanocrystals	Level A	long term	robust interest	sensors	OD3.9
Photonic lantern	Level B	medium term	robust interest	spectroscopy	OD3.9
Vector vortex coronagraph	Level C	medium term	robust interest	detectors	OD3.9
Infrared metamaterials	Level A	long term	robust interest	temperature cycling	OD2.2
Metasurfaces	Level A	long term	robust interest	sensors	OD3.9
Pupil Remapping Interferometer	Level B	medium term	robust interest	inteferometry	OD3.9
Fast randomly addressable reconfigurable metamaterials	Level A	medium term	hot topic	communications, sensors and detectors	OD3.9
Frequency selective surfaces	Level A	medium term	robust interest	antenna design, detectors, sensors	OD3.9, OD4.4
Plasmonic enhanced photosensitivity	Level A	medium term	hot topic	sensors, detectors	OD3.9
Frequency selective surfaces	Level A	long term	robust interest	temperature cycling	OD3.9, OD4.4
Negative index metamaterials	Level A	long term	robust interest	detectors	OD3.9
Phase change films	Level A	long term	robust interest	radiation protection	OD1.6
Planar reconfigurable lenses	Level A	long term	robust interest	sensors	OD3.9
Plasmonic colour separation	Level A	long term	robust interest	sensors	OD3.9

near infrared wavelengths, but there are signs that photonic materials will find powerful applications in the UV and mid infrared. The community envisages a time when whole instruments are embedded in a bulk medium or on a substrate. The first steps in that evolution have already been taken. But a major obstacle at present is the size and shape of pixels on conventional CCD detector arrays.

Applications of photonics proposed for future space missions include laser measurement of the distances between satellites flying in formation, laser communications for interplanetary missions, signal processing and adaptive beam forming. Other major advances are expected in frequency metrology with laser frequency combs integrated into compact optical circuits. Looking further into the future, it is expected that further advances will come from the realisation of the theory of negative-refractive-index materials. It may even be possible to beat the diffraction limit of optical systems in some instances.

The following sections will highlight some new developments in the photonics and metamaterials research field. Due to the immense scope of the term 'photonics', it is impossible to cover everything. A particularly pointed omission is that of laser technologies and their application. This is due to the fact that ESA is quite aware of the developments in the field so a repetition would be unnecessary.

7.1 Photonics on a chip

One of the most active research areas today is the effort to solve the interconnect bottleneck on computers and sensors. The speed and cost of the individual logic elements has been improving steadily over the years, but the performance of the electrical interconnects between the components has not, due to the resistive nature of metal wires. This effectively creates an 'electron bottleneck' that hinders the performance of the circuit. Furthermore, the power consumption and response time of metal wires increases as the line-width of the interconnect decreases with the demands for smaller processors. Effective optical integration on-chip will have to rely on wavelength-division multiplexing to deliver information capacities per footprint that significantly exceed those of electrical wires, with no power-dissipation penalty.

Fibre optics have been used successfully for years to bypass some of the limitations of electric wires. Nevertheless, this method is still 'bulky'. Using optical interconnects and on-chip integration of all elements is one elegant solution to the bottleneck. The appeal of using photons instead of electrons for communication of the chip components are multiple: resistance to electromagnetic interference, low energy consumption per volume of required space and high bandwidth connections (Kirchain and Kimerling 2007; Liu et al. 2010). Unfortunately, fully integrating optics on a chip has not been achieved, since light generation and amplification onto a single silicon chip is still problematic. Commercial wafer scale fabrication of photonic devices has crystallised into several major technologies:

1. III-V semiconductors: InP, GaAs
2. Nonlinear crystals: $LiNbO_3$
3. Dielectrics: Silica, Silicon Nitride
4. Element semiconductors: Silicon on Insulator (SOI)

A current example of the capabilities and advantages of these technologies can be seen in Table 15.

Each technology has specific strengths but integration in a single platform without sacrificing overall system performance has not yet been achieved (Capmany 2013). The field is vast, with an enormous amount of research devoted to it. Details on specific components of a circuit that can be integrated on the chip as optical components can be found in Liu et al. (2010), del Alamo (2011), Lai et al. (2011), Capmany (2013).

The major development for the next decade is expected to be the full integration of photonics on silicon and on III-V compound. It will allow the creation of compact and solid-state chips that could operate much better in radiation rich environments.

Technology Area	Tech Level	Development Horizon	Interest
Photonics on chip	Level C	short term	hot topic

Entry points: Daniel Dolfi (Thales Research and Technology, Physics Department), Daniel Vellou (MINATEC), Marie-Noëlle Semeria (CEA), Pierre Kern (IPAG), Valerio Pruneri (ICFO Barcelona), Nikolay Zheludev (Southampton University), José Capmany (VLC Photonics)

7.2 Photonic crystal fibres

The development of optical fibres (OFs) in the 1960s was the base of a revolution in the broad field of Information and Communications technology. OFs offered an advantage in sensitivity and flexibility on the geometry over pre-existing systems.

Photonic crystal fibres (PCFs) were developed in 1996 and they offer substantial improvements or even novel abilities when compared to traditional OFs. The main difference between PCFs and nor-

Table 15. Capabilities of materials used for optical components, adapted from Capmany (2013); VLC Photonics (2012).

Material Capability	SOI	SiO_2/Si	Si_3N_4/SiO_2	InP/GaAs	$LiNbO_3$
Low propagation loss		X	X		
Good coupling to fibres		X	X		X
Good electro-optic effect				X	X
Good thermo-optic effect	X	X	X	X	
Good electro-absorption effect				X	
Light generation/regeneration				X	
Small footprint	X		X	X	
Compatibility with electronics	X				

mal OFs is that PCFS are constructed from a single material. PCFs rely on closely arranged air holes that go through the whole length of the fibre in order to guide the light inside, whereas traditional fibres utilise spatially varying glass compositions as waveguides (Liu et al. 2010; del Alamo 2011; Lai et al. 2011; Capmany 2013). The fundamental difference between PCF and normal OF is that, instead of internal reflection at the boundary of the core and cladding, light is confined in the PCF by the photonic band gap.

PCFs offer the possibility to tune the fibre transmission spectrum, mode shape, non linearity, dispersion, air filling fraction and birefringence in ways that are not achievable by traditional fibres. This is achieved by varying the shape and spacing of the air holes in the fibre (Pinto and Lopez-Amo 2012). An additional novel ability of PCFs is the possibility to fill the fibre with various gases or liquids. This ability offers novel sensing techniques that were not available with classic fibre design. Another advantage of PCFs is that they can transmit much higher laser powers in single mode without Stimulated Brillouin Scattering in the optical fibre.

Additionally, the fibres can be embedded in aerogel, eliminating the air from them. This provides the fibres with additional thermal resilience (albeit with a loss of flexibility), without any losses on the travelling wave (Xiao et al. 2009).

A list of all the applications of PCFs in sensors can be found in the reviews of Wadsworth, Knight and Birks (2012) and Pinto and Lopez-Amo (2012). Innovation is expected at 10 years scale in the key area of photonic crystals leading to optical fibres with diverse original structures (specialists are in the UK and Germany).

Technology Area	Tech Level	Development Horizon	Interest
Aerogel photonic component packaging	Level C	medium term	robust interest
Photonic crystal fibres	Level C	medium term	robust interest

Entry point: William Wadsworth (Centre for Photonics and Photonic Materials, University of Bath)

7.2.1 Sapphire Photonic Crystal Fibres

Optical fibres are extremely difficult to manufacture for high temperature environments, since the materials that are normally used melt at those temperatures. One approach to tackling this problem is to use optical fibres made out of sapphire, a material with a high melting point (~2045 °C). Sapphire also has excellent mechanical and chemical properties as well as good optical propagation. Sapphire PCFs can find applications in sensors that are required to function in very high temperature environments (>1000 °C), albeit with some length restrictions[15] (Pfeiffenberger 2010; Dragic et al. 2012).

Technology Area	Tech Level	Development Horizon	Interest
Sapphire PCFs	Level C	long term	robust interest

Entry point: Michal Basista (KMM-VIN)

7.3 Micro-resonators

Frequency combs are coherent light sources that emit a broad spectrum consisting of discrete, evenly spaced narrow lines. Traditionally, frequency combs were generated via mode locked lasers and have found uses in metrology and spectroscopy or anywhere where high precision measurements of frequency or time are needed.

A relatively new technique uses a different approach to produce a frequency comb. By using a continuous wave laser source and utilising the non linear optical process of parametric frequency conversion, this is achieved with the help of a compact optical micro-resonator that traps the laser light in a small volume and enhances its intensity and interactions (Kippenberg, Holzwarth and Diddams 2011) sharp spectral lines that form an optical frequency comb is enabling unprecedented measurement capabilities and new applications in a wide range of topics that include precision spectroscopy, atomic clocks, ultracold gases, and molecular fingerprinting. A new optical frequency comb generation principle has emerged that uses parametric frequency conversion in high resonance quality factor (Q. One of the most important classes of micro-resonators are the so-called 'Whispering Gallery Mode' resonators that confine light by total internal reflection around the perimeter of the dielectric interface. The micro-resonators can be made out of fused silica, silicon, glass or crystals and they can be of various symmetrical shapes such as micro-toroids, micro-spheres, micro-rings or micro-disks.

The main advantage of micro-resonators as frequency combs is that they are smaller than frequency combs based on mode-locked lasers and that

15. The maximum length for commercially available sapphire fibres is around 2 m (Photran LLC).

they can have a repetition rate well above the 10GHz range. They especially offer a viable alternative for applications in the infra-red, such as spectroscopy and atomic clocks (Schliesser, Picqué and Hänsch 2012; Wang et al. 2013). They are also more compact, as they can combine the resonator and waveguide on the same chip, with fabrication techniques similar to standard CMOS technology (Kippenberg et al. 2011).

Possible applications include: astronomical spectrograph calibrations, quantum optics and telecommunication (Kippenberg et al. 2011). Micro-resonator frequency combs are still in development phase and although they are not envisaged as a replacement for conventional frequency combs, they can be used for special applications that require high repetition rates and wavelength ranges (Kippenberg et al. 2011).

Technology Area	Tech Level	Development Horizon	Interest
Micro-resonators	Level A	medium term	robust interest

Entry point: William Wadsworth (Centre for Photonics and Photonic Materials, University of Bath)

7.4 Astrophotonics

Astrophotonics is a relatively new field that has emerged through the application of light guiding devices to astronomy (Bland-Hawthorn and Kern 2012). These devices are based on technology developed for the communications industry. They enable a range of new capabilities – from spectroscopy of many targets to be carried out in parallel (multi-object spectroscopy) to new modes of spectrometers that can reduce the size and mass of instruments to the theoretical minimum by manipulating light so that it propagates as single modes through multiple fibres. Some of the most interesting applications for ground based astronomy are for removing the effects of the atmosphere: adaptive optics for cancelling out the effects of turbulence, and OH suppression filters to remove noise and spectral contamination generated by atmospheric absorption lines that are a particular problem at near infrared wavelengths. Although these techniques are obviously not needed for space telescopes, the same technologies could be used to enable smaller instruments in space to reduce payload restrictions. Precision selective filtering could also find applications for efficient detection of specific gases in planetary exploration.

7.4.1 Photonic lantern

If perfectly imaged, a point source object (e.g., a star) can be closely approximated by a single fundamental Gaussian spatial mode. However, if the imaging is distorted by optics, an atmosphere, or if the object is in fact resolved by the optics and no longer point-like, the image of the star will be composed of multiple spatial modes. In this case, it can only be coupled efficiently to multimode fibres. As light propagates through this fibre, the modes follow different effective paths (ray angles), and it is not possible to harness the full power of photonic components, such as Fibre Bragg Gratings (FBGs) or Arrayed Waveguide Gratings (AWGs). To exploit the full power of photonic concepts for processing multimode light, it is necessary to use a device known as a 'photonic lantern' – so called because of its resemblance to a Chinese paper lantern.

The first prototype photonic lantern was demonstrated using techniques borrowed from the photonic-crystal fibre field (Leon-Saval et al. 2005). New routes, relying on advanced laser manufacturing techniques (Thomson et al. 2011) now open the prospect of fully solid-state lanterns that could be integrated with photonics spectrometers and detectors to make fully integrated multimode spectrometers operating at the diffraction limit. Such spectrometers could revolutionise ground based astronomy, since the size of the spectrometer would be independent of the telescope size (all other parameters being equal, e.g., resolution) (Harris and Allington-Smith 2012). This technology would therefore be invaluable when combined with bigger telescopes.

Because the photonic lanterns allow the efficient optical coupling of light into single mode fibres, it is envisaged they will be particularly useful on the ground, where the Point Spread Function (PSF) varies with atmospheric conditions. Nevertheless, these devices could also be important in space for spectroscopy of extended sources, or when there are aberrations caused by segmented mirror misalignment.

Technology Area	Tech Level	Development Horizon	Interest
Photonic lantern	Level B	medium term	robust interest

Entry Points: William Wadsworth (Centre for Photonics and Photonic Materials, University of Bath), Colin Cunningham (UK ATC, University of Edinburgh)

7.4.2 **Pupil remapping interferometer**

Direct observations of exoplanets are a key objective for many ground and space based future telescope projects. Conventional techniques that use coronography to block the light from the host star exhibit limitations on the angular separation (or Inner Working Angle, IWA) of the planet and star at $3\lambda/D$, where λ is the wavelength and D the telescope aperture. This angular separation can be reduced to λ/D using a technique that was proposed nearly thirty years ago (Baldwin et al. 1986): closure phase sparse aperture interferometry. Although the contrast that can be achieved is much less than conventional coronography, it would exhibit the unique capability to directly image young, warm and massive planets at separations from stars similar to those in our solar system. This technique is now starting to become feasible, through the use of ultrafast laser inscription to fabricate arrays of waveguides to remap the telescope pupil in order to form a non-redundant array of sub apertures that are then fed into a spectrometer. A prototype of such a system, operating in the near infrared, has recently been demonstrated on the Anglo Australian Telescope (Jovanovic et al. 2012). While the technique has advantages for use on the ground due to its low sensitivity to phase fluctuations caused by the atmosphere, it would also work well in space, and could be used as one mode of a giant space telescope aimed at exoplanet discovery and characterisation.

In the future, pupil remapping (and other interferometric imaging techniques) must move from the near infrared (as was demonstrated in Jovanovic et al. 2012) to the mid infrared. This move is driven by the fact that the mid infrared contains the so-called molecular 'fingerprint' region, which enables direct detection of biomarkers, but also because the peak of the blackbody emission of earth-like exoplanets at 300 K is at around 10 microns. Importantly, the technology for creating mid infrared beam combiners and pupil remappers using ultrafast laser inscription techniques has now recently been demonstrated through a UK-Germany-France collaboration (Rodenas et al. 2012).

Technology Area	Tech Level	Development Horizon	Interest
Pupil remapping interferometer	Level B	medium term	robust interest

Entry Point: Colin Cunningham (UK ATC, University of Edinburgh)

7.4.3 **Vector vortex coronagraph**

An Annular Groove Phase Mask (AGPM) coronagraph in the mid infrared has been produced and tested on VLT/NACO. The AGPM is an optical vortex made out of a subwavelength grating. The vortex coronagraph is one of the most advanced new-generation coronagraphs and its interest lies in its ability to reach high contrast at very small inner working angles, while maintaining high throughput over a full 360° field of view (Delacroix et al. 2013; Mawet et al. 2010).

Technology Area	Tech Level	Development Horizon	Interest
Vector vortex coronagraph	Level C	medium term	robust interest

Entry Point: Serge Habraken (Applied Research Centre, University of Liège)

7.4.4 **Field Outlook**

Astrophotonics lies at the interface of astronomy and photonics. This burgeoning field has emerged over the past decade in response to the increasing demands of astronomical instrumentation. Early successes include:

1. Planar and three-dimensional waveguides to combine signals from widely spaced telescopes in stellar interferometry
2. Frequency combs for ultra-high precision spectroscopy to detect planets around nearby stars
3. Ultra-broadband fibre Bragg gratings to suppress unwanted background photons
4. Photonic lanterns that allow single mode behaviour using multimode light
5. Planar waveguides to miniaturise astronomical spectrographs
6. Large mode area fibres to generate artificial stars in the upper atmosphere for adaptive optics correction
7. Liquid crystal polymers in optical vortex coronographs and adaptive optics systems.

Astrophotonics, a field that has already created new capabilities in near infrared astronomy, is now extending its reach down to the Rayleigh scattering limit at ultraviolet wavelengths, and out to mid infrared wavelengths beyond 2500nm (Rodenas et al. 2012).

7.5 Metamaterials

Metamaterials (MMs) find use in optical, microwave, radio, heat transfer and other applications. Some of the novel applications that became possible with MMs are imaging with nanometer-scale resolution and the construction of a material with negative refractive index. MMs can also find applications in quantum information systems and nano-optics (Kildishev, Boltasseva and Shalaev 2013).

The most promising classes of new plasmonic materials include materials such as inorganic ceramics [notably transparent conducting oxides (TCOs)] and transition metal nitrides. For example, indium tin oxide and zinc oxide doped with aluminium or gallium have shown promise as a plasmonic material in the near infrared range. In the visible range, intermetallics such as silicides, germanides, borides and nitrides could serve as plasmonic materials (Kildishev et al. 2013).

7.5.1 Metasurfaces

Metamaterials can be utilised to produce metasurfaces, a recent development in MM research. Whereas MM application relies on bulk, multilayered MMs to achieve the desired functionality, metasurfaces are based on the planar photonics concept, controlling light on a flat, 2D surface. This reduced dimensionality allows for new physics and different properties than the 'traditional' 3D MMs. Metasurfaces can be utilised for super-resolution imaging, sensing, data storage, quantum system and light detection (Kildishev et al. 2013).

Metasurface can help overcome some of the pitfalls of MMs production and utilisation as they can be cost-effective to fabricate and easier to integrate in photonic systems. The studies of new building materials for metasurfaces that are made of low-loss, tuneable plasmonic materials (metals or metal-like materials that exhibit negative real permittivity), such as transparent conducting oxides and intermetallics, will enable the creation of novel smart designs and allow for advanced switching techniques. The goal is to produce chip scale devices that are cost-efficient to manufacture, have increased operational bandwidths and significant lower losses. These devices are projected to revolutionise nanophotonics and optoelectronics (Kildishev et al. 2013). These devices are a very active research in photonics and introduce the concept of 'metadevices', where the nanostructures bring new functionalities, in contrast to the metamaterial paradigm where the nanostructures bring new properties for the material (Zheludev and Kivshar 2012).

Technology Area	Tech Level	Development Horizon	Interest
Metasurfaces	Level A	long term	robust interest

7.5.2 Infrared metamaterials

Highly anisotropic hyperbolic metamaterials (HMMs), which are usually made of alternating metal and dielectric layers or using metal wires embedded in a dielectric host, are metallic in one direction and dielectric in the other directions. In HMMs, light encounters extreme anisotropy, causing its dispersion to become hyperbolic. HMMs can enhance the density of states for photons within a broad spectral range. The radiative decay rate for light emitters is proportional to the photonic density of states (PDOS); thus, the radiative decay can be efficiently enhanced in HMMs.

There is ongoing effort to develop quasi-2D highly anisotropic hyperbolic metasurfaces (HMSs) that could offer important advantages over their 3D counterparts because such HMSs would be chip-compatible and would typically have small losses that are relatively easy to compensate. Planar and ultrathin HMSs also offer straightforward device fabrication and integration. HMSs would also provide broadband control over the PDOS.

The enhancement in the PDOS provided by HMSs also enables the engineering of thermal radiation and near-field heat transport. Engineering the thermal radiation of emitters over a broad band of mid infrared frequencies that is enabled by HMSs also allows efficient control over the flow of heat, which is essential for many applications such as surveillance, sensing, detection and imaging (Kildishev et al. 2013). A topical example of thermal management with metamaterials can be seen in the US Air Force contract 'Infrared Metamaterials for Emission Phase Control', awarded to Sandia National Laboratories,[16] with the purpose of designing and testing a directional emission surface that can maintain high emissivity while mounted on a satellite in orbit and using the directed absorption capacity to selectively reject heat loading from the sun or earthshine.

Technology Area	Tech Level	Development Horizon	Interest
Infrared metamaterials	Level A	long term	robust interest

16. http://sbirsource.com/sbir/awards/142233-infrared-metamaterials-for-emission-phase-control

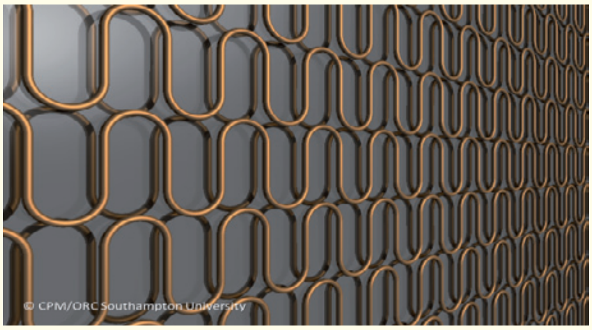

Figure 13. Matamaterial showing magnetic induced transparency. Credit: University of Southampton.

7.5.3 Phase change films

Another interesting application of metamaterials is related to materials that act as perfect absorbers, stemming from the possibility to design metamaterial elements which can individually absorb the electric and magnetic components of incident EM waves (Landy et al. 2008), albeit within narrow range and for low frequencies (Liu and Zhang 2011). There is potential in this field to develop radiation shielding materials.

Technology Area	Tech Level	Development Horizon	Interest
Phase change films	Level A	long term	robust interest

7.5.4 Fast randomly addressable reconfigurable metamaterials

Metamaterials can also serve as modulators. Metadevices have been fabricated that operate in the optical telecommunication range of wavelengths, consuming only a few microwatts of power. These devices can serve as modulators and can also perform non-volatile switching, providing high-contrast transmission change. The main advantage that metamaterial technology can bring to electro-optical modulation is achieving deep modulation in thin, often subwavelength, metadevices. In many cases such metadevices can operate at low voltages, which is clearly a competitive advantage over conventional technology exploiting bulk and expensive electro-optical crystals (Zheludev and Kivshar 2012).

A recent example of such a device was the first phase-change nanocomposite material for nonlinear optics and nonlinear plasmonics. It was fabricated by grain-boundary penetration of gallium into the network of domains of an aluminium film (Krasavin et al. 2006). This optically and temperature-driven composite metamaterial forms a mirror-like interface with silica and shows an exceptionally broadband phase transition-based switching response to optical excitation. It oper-

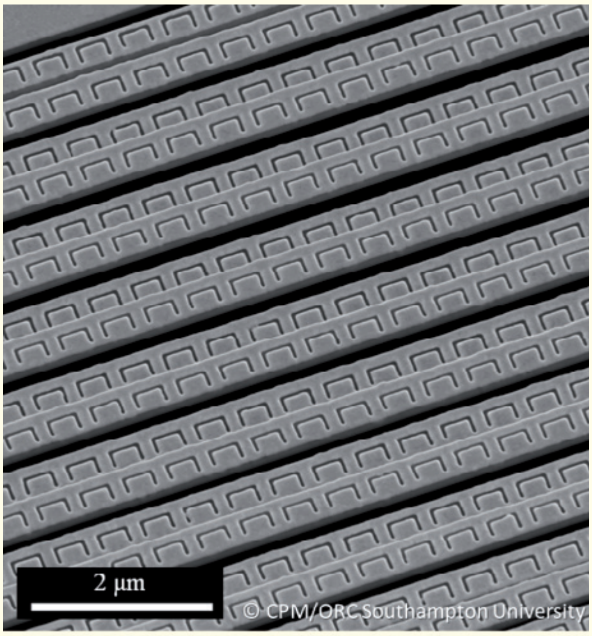

Figure 14. Scanning electron micrograph picture of a thermal reconfigurable metamaterial. Credit: University of Southampton.

ates from the visible to near-infrared part of the spectrum and exhibits ~20% reflectivity change at optical fluence of about 1.5 mJ cm^{-2} with sub-100-ns response time (Zheludev and Kivshar 2012). Enhancement of ultrafast nonlinearities with metamaterials offers the brightest and fastest nonlinear media. There are many potential groundbreaking applications such as terahertz-rate all-optical data processing, ultrafast optical limiters and laser saturable absorbers (Zheludev and Kivshar 2012).

This area of research is expected to produce significant results in the next decade and will probably constitute the most important development in the area of metamaterials.

Technology Area	Tech Level	Development Horizon	Interest
Fast randomly addressable reconfigurable metamaterials	Level A	medium term	hot topic

7.5.5 Frequency selective surfaces

Frequency selective surfaces (FSS) are a relative new paradigm, extending the capabilities of fixed frequency metamaterials that relied on their geometry and cell spacing to determine the response to a fixed frequency range (i.e., antenna and radome elements). Frequency selective surfaces can be either planar 2D periodic arrays of metallic elements with specific geometrical shapes, or can be periodic apertures in a metallic screen. The transmission and reflection coefficients for these surfaces can be dependent on the frequency of operation (or even the polarisation and the angle) of the electromagnetic wave striking the material or the angle of incidence. FSS can operate as stop-bands for certain frequencies and allow wave transmission at others. Novel FSS designs can lead to higher gain for antenna designs (Ranga et al. 2011) or unique filtering profiles (Rashid and Shen 2010).

Metamaterials can also be used as new colour filters. A recent example of a colour filter comprising arrays of subwavelength holes in an aluminium film has been developed. In addition to the simplicity of the process, the aluminium film enables the excitation of visible-range surface plasmons due to its high plasma frequency. Periodic nanostructures in the aluminium film open the way for new visible colour filters (Inoue et al. 2011).

Technology Area	Tech Level	Development Horizon	Interest
Frequency selective surfaces (temperature cycling)	Level A	long term	robust interest
Frequency selective surfaces (antennas, sensors, detectors)	Level A	medium term	robust interest

7.5.6 Plasmonic colour separation

Adiabatically graded metamaterials offer the potential to 'store' photons inside solid-state structures at room temperature. This in practice translates to controlling of the broadband light velocity inside a metamaterial which can have significant application in nanophotonic components, integrated photovoltaic devices, telecommunications, switching applications and biosensors on a chip. This effect is known as 'Rainbow trapping' and has recently been demonstrated for the 500 – 700 nm region (Gan et al. 2011).

Technology Area	Tech Level	Development Horizon	Interest
Plasmonic colour separation	Level A	long term	robust interest

7.5.7 Negative index metamaterials

One of the most exciting (and arguably the most known property of) metamaterials applications is the circumvention of the diffraction limit of conventional lenses. This is made possible with the use of Negative Index Media metamaterials (NIMs) – materials that have a negative refraction index. Proposed in the 1990s, these materials can now be routinely produced for microwave frequencies and have been produced for optical frequencies as well [see Zhang and Liu (2008) and references therein]. This is another important application for HMSs as

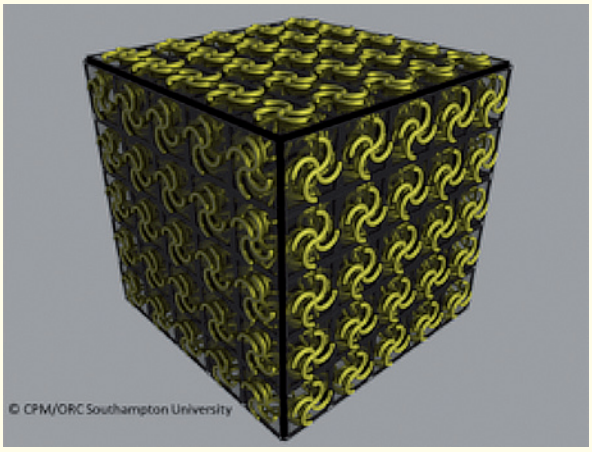

Figure 15. Negative Chiral Index Metamaterial.
Credit: University of Southampton

well, as a surface hyperlens for super-resolution imaging, which was previously proposed and realised for the 3D case (Kildishev et al. 2013).

The chief limitation of present designs of the far field superlens or hyperlens is that the object must be in the near field of the superlens, although the image can be projected into the far field. Practical applications are still possible with the object near the lens (Zhang and Liu 2008).

Researchers are now able to demonstrate different approaches that do not rely so much on the position of the lens extremely close to the sample, while still beating the diffraction limit (Rogers et al. 2012). This new technique is based on super-oscillatory imaging (Rogers and Zheludev 2013) and provides super-resolution without evanescent waves, and therefore without being in the near field of the object.

Technology Area	Tech Level	Development Horizon	Interest
Negative index metamaterials	Level A	long term	robust interest

7.5.8 Plasmonic enhanced photosensitivity

Plasmonic structures can increase photosensitivity significantly and thus can be used for efficient sensing. With metasurfaces, one can increase sensitivity even further. Metasurfaces can transform the local environmental changes into a shift in the angle of the anomalous reflection and refraction. The detection of angular shifts can be substantially more sensitive than the detection of small intensity changes. Thus, metasurfaces could be an efficient way to produce ultrasensitive chemical sensors in the mid infrared (Kildishev et al. 2013).

Graphene, as mentioned in the previous chapter, has attracted large interest in photonic applications owing in particular to its promising optical properties, especially its ability to absorb light over a broad wavelength range, which has led to several studies on pure monolayer graphene-based photodetectors. Recently, a pure monolayer graphene photodetector has been demonstrated with significantly high photoconductive gain, in the region of 8.61 A W^{-1} (Zhang et al. 2013).

Another promising area of development in the area of photodetection is chemically synthesised nanocrystals (NCs). Due to their bandgap tunability and solution processability, they are easy to integrate with any type of substrate, at reduced costs and over large areas. Coupling of NCs with plasmonic nanostructures can enhance their performance even further and increase their broadband sensitivity. This was recently demonstrated for the case of deposited plasmonic silver nanoparticles on a CdTe nanocrystal monolayer incorporated on a metamaterials device. Broadband improvements were observed in the optical region. Plasmonically enhanced nanocrystal skins hold great promise for large-area UV/visible sensing applications (Akhavan et al. 2013).

Technology Area	Tech Level	Development Horizon	Interest
Plasmonic enhanced photosensitivity	Level A	medium term	hot topic

7.5.9 Planar reconfigurable lenses

The concept of 'metalens' has been recently demonstrated in the laboratory. An extremely thin (30 nm) and very small (2 mm in radius) metalens, based on Babinet complementary nanoantennas (V-shaped slots in a metal sheet) was used for extra-strong focusing of light (with a focal length as short as 2.5 mm) in the visible wavelength range (Ni et al. 2013; Roy, Nikolaenko and Rogers 2013). Such lenses can spatially separate light at different wavelengths within small, micrometre-scale areas. Metalenses can serve as easy-to-tune elements for future photonic devices. They can be used for on-chip fabrication or fibre-embedded optical devices, including nanophotonic couplers, ultrathin objectives and micrometre-scale light concentrators (Kildishev et al. 2013). The concept is scalable for IR to UV range and the same lens can be changed and reconfigured for different wavelengths.

Technology Area	Tech Level	Development Horizon	Interest
Planar reconfigurable lenses	Level A	long term	robust interest

7.5.10 Metamaterials outlook

Metamaterial research is a very active field that holds much promise for advancing optoelectronics and microelectronics application. The most prominent limitation is high cost and difficulty in manufacturing. The new generation of metasurfaces have improved on performance issues of metamaterials and have made them easier to integrate in photonic devices (Kildishev et al. 2013). Once the fabrication issues have been dealt with, robust and reliable metadevices will allow photonics to compete with electronics not only in telecommunication systems, but also at the level of 'Photonics Inside' consumer products such as mobile phones or automobiles (Zheludev and Kivshar 2012). A timeline for the field of metamaterials can be found in the recent review from Zheludev (2011).

One of the main characteristics of the metamaterials research field is the ongoing search for a real world application for the metadevices. This has not been identified yet, and researchers in the field are looking for the 'ultimate killer application' that can help in solving one of the grand challenges. Metamaterials for improving solar energy harvesting or metamaterials for novel medical diagnostics are prime candidates (Soukoulis and Wegener 2011).

Entry point (for metamaterials): Nikolay Zheludev (Optoelectronics Research Centre, University of Southampton)

7.6 Conclusions

The commercial applications of photonics integration are poised to drive the telecommunication device market for the future. There are huge developments in micro-detectors for mobile telephony. For example, STMicroelectronics (STM), Europe's largest chip maker, produces 500,000 cameras per day. Everything, including the camera, is smaller than a coin. SIM cards are only a millimetre thick and use only one thin output cable. The commercial market future thus seems to be in very integrated photonics devices, with an optical fibre in input and a USB plug as output. This drive will also impact the sciences and applications that use light as their field of study, such as astronomy, medical imaging, space, telecommunications.

A hybrid approach to funding development, with the definition of some targeted areas for development, is favoured by the nanophotonics community. Consortiums that combine technology makers and

Table 16. Platforms and networks for photonics and metamaterials

Name	Description/Area	Type
Photonics21	Photonics21 represents photonics research & innovation priorities at European level	European Technology Platform
Nanophotonics Europe Association	An independent, not-for-profit, legal organisation to promote European science and technology in the emerging area of nanophotonics	Association
Metamorphose VI	Virtual Institute for Artificial Electromagnetic Materials and Metamaterials	Virtual Institute
European Optical Society	Academic and Industry body	Professional Organisation

end users have worked quite well in the past, since the collaboration bridges any of the gaps present in the technology development.

In order for photonics to realise their full potential as a key technology, more must be done in order to coordinate and integrate the various research efforts that are happening around Europe. The field is vast, covering many sectors and with an enormous amount of effort devoted to it. It is natural then that the fragmentation of R&D effort will result in many promising technologies but will stall in the commercialisation of these technologies (Photonics21 2011).

It must be noted that most of the foundries are or will be located in Asia, despite the fact that European laboratories at the moment are at the forefront of research and demonstration of concepts. It is expected that 80% of the photonics business will go to Asia (MONA consortium 2008; Nikolay Zheludev, TECHBREAK interview).

A problem that arises when considering adoption or use of technology from photonics to the space sector is that most of the experts in the photonics community are not aware of what happens in the space environment and therefore do not understand what the constraints of space applications are. For those involved in the space sector, the problems might be obvious but this is not the case for other scientists and engineers. There is a need to translate the 'space obvious' facts into a language that the non-space people can use. An example that was used during the TECHBREAK workshop was the behaviour of glass in space and a high radiation environment. It is a simple but fundamental problem that the space sector is well aware of but it is not very clear to the photonics community and that information would be vital for metamaterials and photonics research in space.

7.6.1 Future developments in the field

A European–USA workshop on photonics (Roco, Mirkin and Hersam 2011) has highlighted the four major areas that photonics will focus on for the coming decade. These are:

1. All-optical chip
2. Metamaterials that operate in the visible range
3. Single molecule detection for biomedical applications
4. Artificial photosynthetic systems for energy production.

It is expected that significant progress will be made towards these goals in the next decade.

7.6.2 Major European institutes

Europe is in the forefront of photonics and metamaterials research. The European research community is well established and interacting through the Photonics21 European Technology Platform as well as mirror platforms at a national level. The most prominent research centres are represented in the various research networks, associations and technology platforms that are depicted in Table 16.

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8.
Micro and Nano Electronics

"I do not fear computers. I fear the lack of them."
ISAAC ASIMOV

One of the major challenges that the information and communication sector faces today is that hardware is being pushed to its physical limits. The proliferation of cloud technology for computing applications has increased demands on computer systems that need to handle an immense amount of data, with ultrafast processors, while consuming a minimum amount of energy. Personal devices are pushing for smaller yet faster processors, advanced displays and lightweight components. The main driving force of the whole industry (something that is applicable to the photonics field as well) is the reduction of energy consumption and the continuation of Moore's law.

The traditional methods of reducing product size, increasing functionality and enhancing computing capabilities are quickly reaching their limit. The world of silicon is evolving towards the III–V domain, with composed semiconductors: examples include GaAs (power transistors for mobiles), GaN, InP, and beyond the 10 nm. Photonics on silicon and on III-V materials have the advantage of producing compact and solid-state components. Integration of functions on single platform is pursued and nanotechnology advances, coupled with optical components, will offer the necessary breakthroughs to sustain the growth in capabilities for the future.

The future of components technology will be determined by electronic–photonic convergence and short (<1 km) reach interconnection. This direction is triggering a major shift in the leadership of the component industry from information transmission (telecom) to information processing (computing, imaging).

The following sections will highlight some of the major new technologies in the electronics sector, that can potentially also be applied to space systems.

8.1 Advanced Random Access Memory Elements

Traditional RAM elements are refreshed every millisecond and consume a lot of energy. It is possible to decrease energy consumption by using m-RAM or STT-RAMs (magnetoresistive RAM and Spin Transfer Torque RAM, respectively). These new generations of RAM elements do not store information by manipulation of the electrical charges or flows through them; the information is stored instead by manipulation of the magnetic properties of their elements.

M-RAMs work by measuring the electrical resistance of an m-RAM cell. The cell consists of ferromagnetic plates, separated by an insulator. One plate is permanently magnetised, with a particular polarity, whereas the other plates can be set to different polarities. Information is written by manipulating the polarities. Information is read by measuring the resistance of the cell, a property that depends on the combination of the two magnetic fields present in the plates. The first generation of m-RAM is already used on airplanes to make them non sensitive to radiation. However the current generation of m-RAM does not have the required density (m-RAM from EVERSPIN, a spin-off of MOTOROLA[17]) in order for it to be a viable alternative to normal RAM.

STT-RAM uses polarised electrons to influence the polarisation of plates, taking advantage of the spin transfer torque effect, where polarised electrons influence the polarisation of a magnetic field by transferring angular momentum from the polarised current onto the layer. SST-RAM uses less

17. http://www.everspin.com/

Table 17. Micro/nano electronics space relevant technologies

Technology Area	Tech Level	Development Horizon	Interest	Use	OD
STT-RAM	Level C	short term	hot topic	radiation protection	OD1.7
OLEDs	Level C	medium term	hot topic	illumination	OD5.11
Organic photovoltaics	Level B	medium term	hot topic	solar cells	OD1.1, OD3.1, OD4.7
Fully depleted SOI (FD-SOI)	Level D	short term	hot topic	integrated circuits, low power and low cost	OD5.5, OD4.7, OD4.3
Silicium 3d	Level D	short term	hot topic	miniaturisation, performance increase in electronics	OD3.9
Cryoelectronics	Level A	long term	niche area	sensors	OD3.9
Flexible electronics	Level B	medium term	hot topic	bio-sensors, stress monitoring	OD5.5
Smart networks	Level B	short term	hot topic	robotic swarm	OD4.5
Biological monitoring systems	Level A	medium term	robust interest	crew monitoring	OD5.5
Truly autonomous agents	Level A	medium term	robust interest	self-healing spacecraft, advanced formation flight, new exploration paradigms	OD2.5, OD3.5, OD4.5, OD4.7

current for writing than m-RAM while the reading power remains the same.

The new generation of STT-RAM is close to commercialisation, which will seek to replace d-RAM and S-RAM. The CROCUS company in Grenoble is developing this type of memory, so the research can pass from pure R&D to the level of applications. The new STT-RAM is projected to be implanted in general personal computers in the next few years (Albert Fert, TECHBREAK interview). The rest of the world is fast in capitalising on this technology, with the recent example of RUSNANO incentives to European companies to install manufacturing plans and R&D labs in Russia, in order to transfer the technology to Russia (European Commission 2011).

One of the biggest advantages of m-Ram and STT-RAM is that it offers much better radiation protection than traditional RAM elements. See Wolf et al. (2010) for a review of new techniques for magnetic RAM storage.

Technology Area	Tech Level	Development Horizon	Interest
STT-RAM	Level C	short term	hot topic

Entry Point: Albert Fert (Laboratory III-V)

8.2 Organic light-emitting diodes

Organic electronics, in the form of organic light-emitting diodes (OLEDs), have become the standard technology for producing mobile phone display screens. Apart from a very good image quality, they have a very fast response time (1000 times faster than LEDs) and low power due to their not requiring back illumination, i.e., using an additive rather than subtractive technology. An environmental and strategic advantage is that OLEDS contain no rare-Earth elements.

In the future, OLEDs are set to revolutionise lighting and signage. Unlike LEDs that are point sources, OLEDs are essentially surface emitters. OLEDs could cut lighting-related energy use by 50-90% and can create effects that no other technology can, such as walls or transparent windows that light up after dark. OLEDs have another big advantage in that they can be printed. This reduces production costs and offers almost limitless design freedom.

The immediate aims of ongoing research are to:

- Enable the processing of robust, large area OLEDs on flexible metal and plastic foils
- Develop device designs that minimise the number of process steps for OLED foils
- Provide a low-cost alternatives to indium tin oxide for transparent electrodes

- Optimise top and bottom emission configurations and light out-coupling.

The end goal is to enable OLED applications with lower cost of ownership, greater versatility, more pleasant light, longer lifetimes and very low energy needs. OLEDs can therefore find use in advanced crew habitat management and architecture.

Technology Area	Tech Level	Development Horizon	Interest
OLEDs	Level C	medium term	hot topic

Entry Point: Daniel Dolfi (Thales Research and Technology, Physics Department) and Herman Schoo (TNO-Holst Centre, Eindhoven)

8.3 Organic photovoltaics

Organic photovoltaics (OPV) is a fast emerging research area, with an increasing number of active groups involved. While currently less efficient at converting energy than their traditional silicon counterparts, OPVs offer many advantages that make them an attractive proposition for the solar market. They can be made flexible, lightweight and are potentially much less expensive to manufacture than flat-panel, inorganic solar cells. OPVs can be produced on very thin substrates and thus have very low mass. OPVs on 100 micron substrates are very practicable. Experimental OPVs have been produced on substrates as thin as 20 microns. Whilst these are somewhat fragile for ground based applications, these could provide an interesting solution in space without gravity or wind. The ability to print OPVs in a continuous process means that a larger area can compensate for a reduced efficiency. **Additionally, an OPV can simply be rolled up for launch and unrolled in space.**

Current research into OPVs is aimed at several goals:

- To improve the power conversion efficiency (raising efficiencies from current world record of 6.7% to 10-12% in the next three to five years)
- To improve lifetime and investigate degradation processes
- To develop new and improved technologies for making reproducible, high yield and large area OLEDs at very low cost.

The lifetime of OPVs in a space environment is an important issue to be investigated for future application on space missions.

Technology Area	Tech Level	Development Horizon	Interest
Organic photovoltaics	Level B	medium term	hot topic

Entry Point: Herman Schoo (TNO-Holst Centre, Eindhoven)

8.4 Fully depleted silicon on insulator (FD-SOI)

For decades most microprocessor chips have been built using bulk CMOS technology. But today chipmakers are increasingly constrained by the inability to meet the processing and power consumption needs of portable electronics. CMOS transistors 'leak' current even when turned off, reducing battery life and creating the need for an alternative approach – ideally one that does not require wholesale changes to chip design and production for the 28 nm technology node and beyond.

Fully Depleted SOI is a technology which is utilised in the fabrication of transistors. It relies on an ultrathin layer of silicon, on top of a buried oxide. The transistors built on top of the silicon layer can be ultrathin with excellent noise characteristics, operating with lower power than normal transistors. This is due to the fact that the thin silicon layer does not carry any charges (it is fully depleted).

This technology offers the possibility for the realisation of ultrathin transistors that operate with low power and producing low noise. They offer better control of the logical gates, since there are no charges from the silicon and the manufacturing processes are compatible (albeit more challenging in the integration) with standard CMOS techniques and optimised designs for bulk CMOS can be applied to FD-SOI circuits as well (Cauchy and Andrieu 2010).

FD-SOI transistors drastically reduce electron leakage from the channel to the substrate and thus make the chip operating temperatures lower than normal bulk CMOS. This technology is poised to make a market breakthrough in the coming years, as it offers major enhancements in the area of mobile devices, namely lower energy consumption for the integrated circuits, while maintaining or even enhancing performance over 'traditional' integrated circuits. Additionally, FD-SOI technology can facilitate the production of 3D integrated chips (Batude et al. 2013). The fabrication of a monolithic pixel x-ray detector utilising FD-SOI technology has been demonstrated (Miyoshi et al. 2013).

The technology can find potential applications in very sensitive detectors.

Technology Area	Tech Level	Development Horizon	Interest
Fully Depleted SOI (FD-SOI)	Level D	short term	hot topic

Entry point: Daniel Vellou (MINATEC), Marie-Noëlle Semeria (CEA)

8.5 Silicon 3D

3D stacking of electronic chips is another method of getting more performance out of existing circuit designs. The integration of silicon devices in three dimensions has the benefit of shrinking the size of the electronics, speeding up operations (via shorter pathways and interconnects), increasing power efficiency and decreasing the cost of production (Knickerbocker et al. 2008). This research area is very close to commercial large scale production of 3D integrated electronics that promise to continue offering improved performance from traditional CMOS materials and techniques (Knickerbocker et al. 2008; Lee and Chakrabarty 2013). 3D integrated electronics may not offer the overwhelming improvements that optics-on-chip promise; nevertheless they are closer to commercial availability.

A noteworthy development is the production of a 3D integrated silicon sensor for the 3D ATLAS detector of the Large Hadron Collider (LHC), expected to come on line in 2014. This sensor is going to be inserted as a new layer inside the already existing ATLAS experiment sensor. The detector proximity to the interaction point with the proton beam (3.4 cm distance) necessitated new radiation hard technologies for both sensors and front end electronics. The latter, called FE-I4, is processed at IBM and is the biggest 3D silicon front end ever designed with a surface of 4 cm^2 (Da Via et al. 2012).

Technology Area	Tech Level	Development Horizon	Interest
Silicon 3D	Level D	short term	hot topic

Entry point: Daniel Vellou (MINATEC)

8.6 Flexible electronics

In the field of electronics, the major research efforts are concentrated on making things smaller. Nevertheless, there is also a different path to explore, that of making electronics flexible. Normal silicon wafers are not stretchable or bendable. Research efforts for creating flexible displays and wearable sensors have been going on for the last two decades but the recent advances in nanomaterials and novel semiconductor manufacturing techniques has boosted current research efforts (Rogers, Someya and Huang 2010).

There are two approaches for designing flexible electronics. The first is to construct ultrathin silicon circuits (utilising new electronic materials such as CNTs, nanowires or graphene) that can be embedded in elastomeric substrates. These substrates are shaped in a way as to allow flexing, stressing and compressing. This technique relies on the fact that bending strains decrease linearly with the thickness of the material.

The second method utilises materials that stretch to create circuits, using elastic conductors as electrical interconnects. The most successful method so far has been to use single-walled carbon-nanotubes (SWCNTs) as conductive dopands in a rubber matrix and create a substance called 'Bucky Gell' (Sekitani et al. 2008; Rogers et al. 2010). This substance can then be printed onto elastic sheets to produce electrically conducting materials that are almost 100% stretchable.

Flexible electronics have many uses, especially in the biomedical and sports industries, where they can be used to produce sensors that are embedded in wearable items such as clothes, underwear or accessories, in order to monitor vital functions or environmental parameters whilst being out of the way of the user or patient (Rogers et al. 2010; Zysset and Kinkeldei 2010). One important implementation of wearable sensors is the Body Area Networks, a system of small, easy to wear body sensors that can be used for health monitoring. The advancements in flexible electronics will allow the transition to sensors that are invisible to the user and allow true 'anytime, anywhere' monitoring (Chen et al. 2010).

Other uses potentially include flexible components for electronic devices, flexible antennas and screens, as well as flexible, adhesive stress tensors for structures, flexible photovoltaic and thermoelectric components (Rogers et al. 2010) and heads up displays [see, for example, the heads up display for cars, created at ICFO Barcelona (Patent ES 201131704), shown in a previous chapter, in Figure 7].

Additionally, small and flexible circuits can be deposited on the human skin by soft contact, much like a temporary tattoo or a bandage aid. These epidermal electronics also take advantage of the new techniques for making electronic components small enough to be included in a small area in the skin (D.-H. Kim et al. 2011). These epidermal circuits (that can incorporate a small radio transmitter) can be used to monitor electrophysiological activity in the

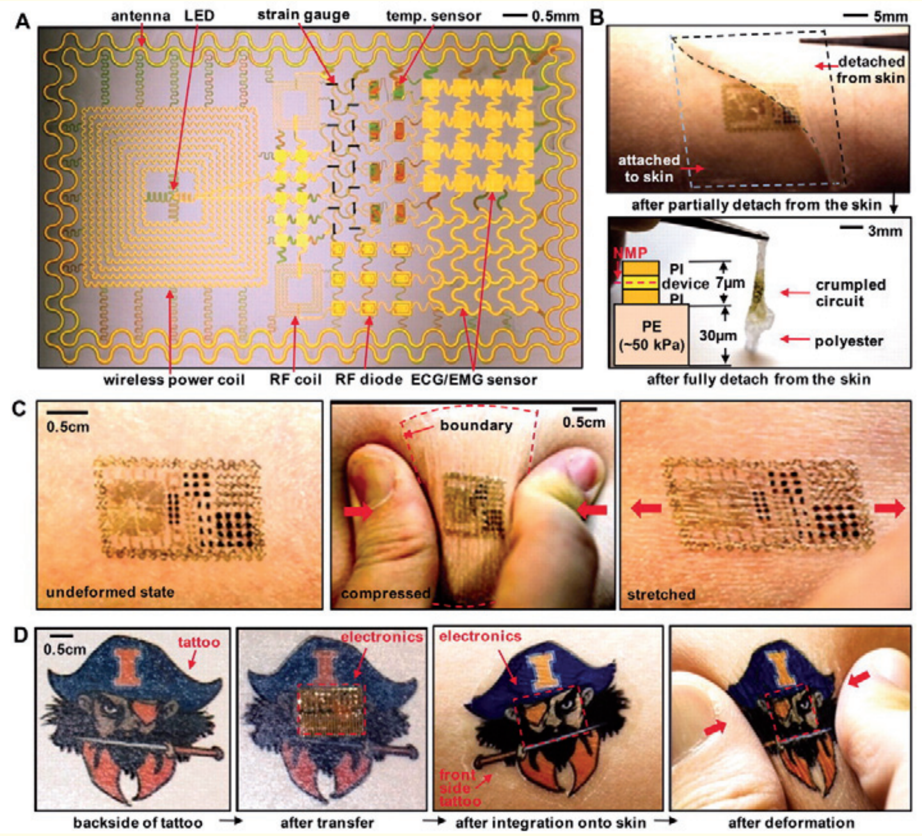

Figure 16. (A) Image of a demonstration platform for multifunctional electronics with physical properties matched to the epidermic, known as an Epidermal Electronic System (EES). (B) EES partially (top) and fully (bottom) peeled away from the skin. (Inset) A representative crosssectional illustration of the structure, with the neutral mechanical plane defined by a red dashed line. (C) Multifunctional EES on skin: undeformed (left), compressed (middle), and stretched (right). (D) A commercial temporary transfer tattoo provides an alternative to polyester/PVA for the substrate; in this case, the system includes an adhesive to improve bonding to the skin. Images are of the backside of a tattoo (far left), electronics integrated onto this surface (middle left), and attached to skin with electronics facing down in undeformed (middle right) and compressed (far right) states.
Image and caption from D.-H. Kim et al. (2011).

brain, heart and muscles without the need for the traditional electrodes that need to be mounted and maintained in position on the body.

It is expected that the cost price (€/m²) will decrease in the next decade, which will make large volume applications attractive and lead to widespread application of the technology. The shift towards stretchable device systems will further enhance wearability and (mechanical) robustness of systems that incorporate the technology (Herman Schoo, TECHBREAK interview). Flexible electronics might also gain pace, especially if they find applications in the clothing industry and thus increase the demand for such products.

The main European research centres in this topic are the Fraunhofer institutes, VTT in Finland and Holst Centre in The Netherlands.

Technology Area	Tech Level	Development Horizon	Interest
Flexible electronics	Level B	medium term	hot topic

Entry points: Marie-Noëlle Semeria (CEA), Valerio Pruneri (ICFO, Barcelona), Herman Schoo (TNO-Holst Centre, Eindhoven).

8.7 Cryoelectronics

In the field of cryoelectronics efforts are made towards the goal of detection of single photons or detection at photon scale at all wavelengths. This has met with success in high frequencies (UV) and is theoretically possible in the optical range as well. Due to the materials used for the electronics, detection is more complicated at lower frequencies. So far, field effect transistors at low temperatures have been used, based on III-V material (Liang et al. 2012; Grémion et al. 2008). This technology can play a significant role in astrophysical sensors that require extremely low temperatures.

Technology Area	Tech Level	Development Horizon	Interest
Cryoelectronics	Level A	long term	niche area

Entry point: Jean-Yves Marzin (CNRS-INSIS)

8.8 Smart networks

The information age of today's world is also a very energy demanding age. Modern lifestyle incorporates a plethora of electronic devices such as mobile phones, computers, laptops, tablets that are interconnected via the internet or other wireless networks. The amount of data present in those networks is also increasing, according to the quality of the sensors available to these networks (mobile phone cameras, HD TV, video recording of mobile devices, etc.). The data streams from these devices will only increase as they improve in quality. The immediate future will also incorporate other devices on these networks as well, such as sensors that are mass produced and cheaply available (sensors on clothes, video cameras, etc.). The trend everywhere is towards more data. Wireless communications are projected to be the major energy consumption source in the world in a few years (Mancuso and Alouf 2011) as well as a heavy polluter.

One of the effects of this 'data deluge' is a massive electricity bill for the network providers and ever increasing demands for server farms that are energy efficient. The efforts in nanotechnology and electronic manufacturing will, without a doubt, provide hardware that is more efficient and will reduce power consumption, but dealing with the power consumption as strictly a hardware problem will not solve the issue. An additional measure is to seek optimisation of the architecture of these networks that will make them energy aware and could result in a 50% increase in power efficiency (Bolla et al. 2011).

Another emerging aspect is the 'internet of things', which is a growing revolution going hand in hand with miniaturisation: energetic autonomy of components, communication capacities, services to the citizen, medical devices, etc. There is a considerable development of 'big data', with important data flows for computation segmentation and memory in several layers. Internet of things is the future with circuits everywhere, communicating between themselves. The data transfer technologies are developing quickly with HP and IBM on the front lines.

In the future, given the trend for miniaturisation of sensors, this can also be an issue for biomedical applications (monitoring of astronauts) or the operation of swarms of sensors or satellites, where measurements will rely on multiple smaller sensors.

The main game changing aspects expected from this paradigm shift will be at architectural level: the objective is to take away the energy spent in switching, in order to make communication more efficient between the components/subnetworks. This will lead to reduced number of switches and thus reduced energy dissipation. The concept of energy aware operation is thus emerging.

Furthermore, in microprocessors in particular, energy is always on. The objective is to gate the power and turn on and off the transistors which are not used. Essentially the objective is to stop spending energy when it is not useful. This is the concept of 'self aware computation'. The same thing applies in telecommunications, with dynamic provisioning, in order to save energy.

A similar concept has emerged in sensor networks. Sensing devices also consume power and maximising the lifetime of their power source is essential. Power optimisation for sensor networks has also received significant attention, especially in the mobile phone industry (Joon Kim et al. 2010), as well as various scientific disciplines that utilise large number of sensors scattered in the field, such as oceanography, biology and environmental monitoring (Benson et al. 2010).

Technology Area	Tech Level	Development Horizon	Interest
Smart networks	Level B	short term	hot topic

Entry point: Bruno Mourey (LETI, Optics and Photonics Department)

8.9 Biological monitoring systems

Biological monitoring systems allow continuous and unobstructed monitoring of many body functions. Such systems would be indispensable for long manned space missions. Interesting technologies include:

8.9.1 Low power wireless communication

An immediate target is to reduce the power requirements for wireless communication such as required for the monitoring of biological functions. As these applications require low bandwidth (<1 Mbps), the goal is to reduce power consumption by an order of magnitude from today's levels. Ultimately, the target is to design transceivers that enable 200 kbps channels (equivalent to Zigbee) with a power consumption of just 200 μW. That equates to 1 nJ/bit, or a factor of 100 lower than Zigbee. These transceivers could in many cases run from scavenged or 'harvested' power from thermal gradients, local light, RF or vibrational sources. The same energy efficiency is expected for bandwidths up to 50 Mbps. In addition to ultra-low power transceivers, research is being done in the Holst Centre for the development of 'wake-up' radios with continuous power consumption below 50 μW. These devices continuously monitor communications channels for wake-up signals, allowing the main radio system to be powered down when not needed to extend energy resources.

8.9.2 Body monitoring systems

Body Area Networks (BANs) are being developed to enable 'anytime, anywhere' health and well being monitoring. These connected systems of smart, highly sensitive, miniaturised sensors can be worn comfortably and continuously measure vital signs and brain activity without disrupting normal activities. BAN systems would use the lower power communications and analysis systems mentioned above. Within the next few years the goal is to combine these technologies to create and validate demonstrators, to explore the potential of BAN applications, better assess end-users' needs and to validate new technologies through real-world tests (Chen et al. 2010; Pantelopoulos and Bourbakis 2010).

As a step towards the full BAN system, the Holst Centre is developing a 'health patch' that is comfortable to wear and can reliably monitor multiple health-related parameters. Eventually this could include ECG, motion, respiration and body fluid analysis sensors. The target power consumption is around 100 μW.

More specific information on the actual sensors integrated in these systems will be given in section 9.1.

Technology Area	Tech Level	Development Horizon	Interest
Biological monitoring systems	Level A	medium term	robust interest

Entry point: Herman Schoo (TNO-Holst Centre, Eindhoven)

8.10 Robotics – Truly autonomous agents

The field of robotics is difficult to place accurately within the contents of the defined KETs. It is a multidisciplinary field that it is itself an enabling technology. For the purpose of the TECHBREAK report, it is placed within the electronics KETs, due to the lack of information and communication technology as a distinct KET within the report.

Robotics is, of course, not an unknown technology for the space sector. Spacecraft can be considered as robots, planetary rovers are amongst the most advanced robots ever created and there are numerous examples of utilisation of robots in the ISS. Nevertheless, in all cases, there is limited autonomy in the actions performed, as most of the decisions are either preprogrammed or directed by human operators on Earth.

The lack of autonomy on decision making presents several problems for spacefaring robots:

- Low level operations, which are often tasks that are repeated many times, may need to be managed by a human operator, requiring significant resources on-board and in the control room, making these processes inefficient;
- In the case of robots operating far from Earth, the reaction time is limited to the time it takes for signals to propagate to Earth, be analysed, and the appropriate response be communicated back to the robot.

Increased autonomy would thus enhance flexibility, response time and adaptation to unknown/unpredicted situations. That would, in turn:

- Allow more complex scenarios to be realised
- Decrease the communication load on deep space missions
- Increase complexity of space operations
- Assist in scientific data management of missions
- Reduce the possibility for operational bottleneck in the control centre due to an emergency situation and
- Enhance unpredictable events response management.

The main paradigm for enhancing autonomy is to shift part of the decision making processes to the on-board instruments through intelligent/autonomous agents. An autonomous agent is simply defined as any part of the spacecraft that can perceive environmental inputs through sensors and act upon that input. Current generation robots operate within a 'top-down' autonomy paradigm, where the decisions made by the autonomous agents have been preprogrammed into them. That of course requires the programmer to be aware of every possible situation to be encountered.

In order to pass to true autonomy, agents that can successfully react to an unknown environment, a new 'bottom-up' autonomy paradigm is necessary. The agents need to perform actions based on their perception, within a very short time horizon and without much prior knowledge. A means for the agents to learn from experience is also needed, to continuously improve the system's response.

The number of autonomous agents that will be required for a complex mission is large and in order to give the system the ability to re-plan the mission goals autonomously, according to the situations encountered (thus achieving E4 autonomy level, according to the ESA mission's autonomy requirements), it is necessary that the agents communicate and act together.

Multiple Agent Systems (MAS) may contain identical autonomous agents (a swarm of robots) or agents that perform different tasks (spacecraft made of 'intelligent' sub-systems) or a combination of both (main control craft with a swarm of robots). A significant effort is being made in modelling MAS with behaviour similar to biological systems. The main goal is to create a robotic system that mimics the decision making process of living organisms that display "*an emerging collective intelligence of groups of simple and single entities*" (Bonabeau, Dorigo and Theraulaz 1999). This so called 'swarm intelligence' is a way to replace the centralised control or decision making with the emerged global intelligent behaviour of a group of individual agents that respond to environmental inputs. These agents react to the environment in a simple way, with a relatively simple set of rules and only a partial view of the world, but the communication and coordination of all the agents of the system allows the system itself to display intelligent behaviour and achieve global objectives.

There are several biological systems that provide such inspiration. Most famous cases are the behaviour of social insects such as ant and bee colonies where, for example, food foraging behaviour for the colony as a whole is a very efficient procedure that quickly identifies the optimal food locations, from the individual actions of its members. Inspiration has also been found in packs of grey wolves, shoals of fish, birds, bacteria and human genes regulatory system [see the reviews of Mohan and Ponnambalam (2009), Şahin (2005), Di, Serugendo and Karageorgos (2006) and the work of Jin, Guo and Meng (2009) and references therein for more information on various algorithms and approaches].

Swarm intelligence arises from coordination of the individual agents and does not rely heavily on decision making algorithms. It uses positive and negative feedback mechanisms to regulate the system's behaviour. Adaptation to dynamic environmental evolution is also done by utilising a combination of feedback mechanisms and stochastic fluctuations of individual behaviour, coupled with interactions between the individuals (Leitão, Barbosa and Trentesaux 2012).

MAS have found use in industrial automation, in order to provide robustness and re-configurability. They have been used for assembly, layout optimisation, scheduling, control and supply chain management among others, exhibiting improvement over 'traditional' decision making techniques. Please refer to the review of Leitão et al. (2012), tables 1 and 2 of said report, for numerous examples of biologically inspired models and applications to industry. Vokřínek, Komenda and Pěchouček (2010) give an example of MAS navigation in an unknown urban environment, whereas Caiti et al. (2013) give details of a system of control for autonomous underwater vehicles for security and exploration.

Parallel to the work on multiple individual agents, there is also research focused on modular, self-assembled robot systems. These robotic systems are able to reconfigure their shape, in order to adapt to a new environment. The modules that comprise the overall system act collectively to change the overall shape or repair any damage done to the ensemble. The idea behind this research is, as is the case of swarms, to increase versatility, robustness and lower cost by producing many, inexpensive units that are part of a system where the sum is more than the individual parts. The future objective is to create systems that can self replicate, are resilient and autonomous and are able to achieve many functions by re-configuring a given number of basic modules (much like a Lego kit). The review of Yim et al. (2007) highlights some proof of concepts in this regard.

As mentioned in the chapter on the Overwhelming Drivers, especially in sections 3.3 and 3.4, this capability would enhance space exploration efforts considerably by, for example, allowing the self assembly of large structures from many small parts acting in unison, allowing exploration of planetary bodies by the utilisation of numerous small and inexpensive robot-probes acting as an intelligent swarm, self-healing structures in space that repair themselves from inexpensive 'bulk' parts and many other possibilities.

Despite some working applications, the main challenges are yet to be overcome, at least for achieving true operational autonomy in unknown environments. Specifically, control of a high number of modules/agents (>1,000), self-replication, self-repair and self-sustaining systems for long periods of time are far from being realised.

Technology Area	Tech Level	Development Horizon	Interest
Robotics – truly autonomous agents	Level A	medium term	robust interest

Entry Points: Michèle Lavagna (Politecnico di Milano)

8.11 Conclusions

In this area, the European position is once again very similar to other fields. European research is world class but the industrial production is carried out in the USA and Asia. A similar situation exists with spintronics research and graphene production. The main projects are in Asia and in the USA, with factories in Russia and China. A significant exception is in the area of semiconductors on thin films and low energy consumptions microprocessor for multimedia applications, where STMicroelectronics are at the forefront of the technical and economic world race.

The European problem thus remains how to finance the technological research and also solve the Death Valley problem. A current trend is to increase the role of large centres with shared resources and international centres between countries. European programmes have thus far not worked very well, with the consortia being rather large, with strong concurrence in research and too small budgets. Fragmentation of companies and laboratories in separate advanced areas is also an issue as this makes joint development difficult. Here a joint EU-ESA approach to this problem could help.

There are university initiatives on fundamental research with centres of excellence: in Germany since 2006, in France with *Grand Emprunt, poles d'excellence* (IDEX), *laboratories d'excellence* (LABEX), in the UK with Oxford and Cambridge Universities, and in Switzerland with EPFL and ETH. The ERC (European Research Council) has strongly influenced the process by awarding slices of 1 M€ on a single person. Derived from the ESF EURYI grant scheme, this system gives a fellowship of five years with total freedom and is very efficient, mostly for young people.

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9. Biotechnology and Medicine

"It is far more important to know what person the disease has than what disease the person has."
HIPPOCRATES

The last part of the interesting technologies within the European KETs is mainly focused on the human factor in space, namely the astronaut crew. There are two main themes in the technologies described in the following sections: monitoring the crew and the environment, and treatment of medical issues. Biochemical and nanoenhanced sensors are utilised for the monitoring of vital signs as well as other environmental factors (which do not require coupling to the crew, but they will be mentioned here nevertheless).

One of the main traits of the technological evolution in this key sector is the proliferation of rapid sensing techniques (concerning ground based applications), especially for medical applications. The main objective is to be able to quickly and effectively detect either environmental agents, vital signs or disease carriers and to do this, if possible, with a simple and cheap sensor. That will allow persons working in the field to avoid having to either utilise expensive equipment or to send samples to the laboratory and wait for the results. As a result of this 'decentralisation', the congestion in laboratories will be alleviated (something very important for hospitals) and the 'point-of-care' personnel will be empowered, with the results that they need being provided to them by small and portable equipment. Biosensing technologies will reach single-molecule resolution, while still being rapid, easy-to-use, compact and cost-effective. Such technologies will first be developed for *in vitro* applications (finger-stick sampling) and in the longer term also for *in vivo* applications (real-time biochemical monitoring).

Another very important trend in the medical domain is the advancement of personalised medicine. Monitoring the health of the crew and responding to the various stress factors is obviously one of the highest priorities and thus interaction of environmental factors with genetics is examined, in order to provide personalised health care, tailored to each crew member.

That would make for a much more effective preparation period as well as increased crew performance during missions.

Table 18. Biotechnology and Medicine, space related technologies

Technology Area	Tech Level	Development Horizon	Interest	Use	OD
Biological and environmental sensors	Level B	short term	hot topic	crew monitoring, blood sampling	OD5.6, OD5.5
Human stress factors	Level A	long term	robust interest	astronaut treatment	OD5.2, OD5.5
Torpor and hibernation research	Level A	long term	niche area	long duration flights, containment for seriously injured crew	OD5.2
Nanomedicine (treatment)	Level D	medium term	hot topic	drug delivery, localised treatments	OD5.4
Synthetic life	Level A	long term	robust interest	drug delivery, life support system, food production, biosensors, in situ resource utilisation	OD5.4, OD5.2, OD5.6, OD4.7

9.1 Biological and environmental sensors

The technologies for sensing particular molecules or groups of molecules have advanced rapidly in recent years. This, coupled with advances in nanotechnology, has led to a game change in the state of the art. In many cases, the established laboratory methods for analysing trace elements and compounds, such as gas chromatography and mass spectrometry, have been augmented or replaced by micro- and nano-sensors with sensitivities down to a single molecule.

More efficient diagnostic tools can be expected for enabling rapid gene expression and epigenetic analysis. In addition, new *in vivo* and *in situ* monitoring sensors will be important for facilitating the early and non-invasive adaption processes and pathology. Sensors for the analyses of exhaled human air, for example, will allow the identification of critical health relevant markers.

Nanotechnology enhanced medical devices can also help in reducing or simplifying the bio-measurements and diagnostics of astronauts. The purpose is two fold: increase of sensor capability as well as reduction of weight by using lighter instruments.

A wide range of technologies is being investigated by many research groups in both industry and academia [see the reviews from Holford, Davis and Higson (2012) and Chin, Linder and Sia (2012), for example]. In Europe, the Philips Research Labs and the TNO Holst Centre, both located on the Eindhoven High-Tech Campus, are key players in this field. Some examples of sensor technology developments are given below.

9.1.1 Electrochemical sensors

Electrochemical sensors have the potential for detecting gases and ions in solution (Hagleitner et al. 2001)and to the design of arrays consisting of different partially selective sensors that permit subsequent pattern recognition and multi-component analysis. Simultaneous use of various transduction platforms has been demonstrated, and the rapid development of integrated-circuit technology has facilitated the fabrication of planar chemical sensors and sensors based on three-dimensional microelectromechanical systems. Complementary metal-oxide silicon processes have previously been used to develop gas sensors based on metal oxides and acoustic-wave-based sensor devices. Here we combine several of these developments to fabricate a smart single-chip chemical microsensor system that incorporates three different transducers (mass-sensitive, capacitive and calorimetric. For example, there are several groups working on sensors that are coupled with a wireless node that function as an easy-to-use sensor to analyse sweat (Poh, Swenson and Picard 2010; Salvo et al. 2010; Schazmann et al. 2010). Miniaturised sensors have also been created for measuring cortisol – an important indicator in stress monitoring (Kaushik et al. 2014). There is significant work conducted on this topic in many European centres.

9.1.2 Resonator-based sensors

Compact, power-efficient, micro- and nano-resonator based sensor systems have the ability to identify complex volatile mixtures in the environment by collectively analysing signals from an array of high-sensitivity, partially selective receptors – in a similar way to the olfactory system (Röck, Barsan and Weimar 2008). These sensors have demonstrated that microbridges with integrated transducers can be coated with absorbent polymers to detect volatile compounds at low concentrations (Lang et al. 2007). By using different coatings on identical resonators, selective sensing of mixtures of compounds can be achieved (Gervais, de Rooij and Delamarche 2011). A review of such sensors can be found in Waggoner and Craighead (2007). Examples of commercialised products can be found in breath analysers for the auto industry[18] and the soon to fly E-nose for the ISS.

9.1.3 Metal-oxide and GaN-AlGaN based sensors

Several gas sensing devices based on ultrathin metal oxides and high electron mobility layers have been developed. For example, a wireless system has been demonstrated that uses GaN-AlGaN-based sensors that are capable of detecting NO_2 in ambient air at concentrations down to 15 parts per billion (Offermans, Crego-Calama and Brongersma 2010). Another promising area is sensors based on nanocrystals and metal oxide field effect transistor systems that enable room temperature gas monitoring (Comini et al. 2009; Fleischer 2008). Some of these highly sensitive sensor concepts can be made more selective by chemically modifying surfaces with self-assembled mono-layers (Karabacak, Brongersma and Crego-Calama 2010).

9.1.4 Optomagnetic biosensors

Philips Research has developed a novel optomagnetic immunoassay[19] technology that is three orders of magnitude more sensitive that current enzyme-based assay technology commonly used to measure

18. http://www.vandf.com/applications/medical-applications.html
19. An immunoassay is a biochemical test that measures the presence or concentration of a macromolecule in a solution through the use of an antibody or immunoglobulin.

blood glucose, for example (Ranzoni et al. 2011). The technology is based on nanoparticles that are magnetically actuated and optically detected in a stationary sample fluid. The dynamic control of nanoparticles by magnetic fields impacts all key immunoassay process steps, yielding unprecedented speed, assay control and seamless integration of the different assay process steps. This method is currently carried out in vitro on finger-prick blood samples; it is expected to be developed as an in vivo sensor [see also the review of Bruls et al. (2009)]. Similar sensors are being developed utilising plasmonic principles, based on surface plasmon resonance physics (see also section 5.2) (Brolo 2012; Zijlstra, Paulo and Orrit 2012).

Technology Area	Tech Level	Development Horizon	Interest
Biological and environmental sensors	Level B	short term	hot topic

Entry point: Herman Schoo (TNO-Holst Centre, Eindhoven), Alexander Choukèr (LMU Hospital, Munich), Daniel Vellou (MINATEC), Menno Prins (Technical University Eindhoven / Philips)

9.2 Human stress factors

For manned space flight, a large number of problems need to be addressed that are not encountered with unmanned missions. These not only concern technical issues like the provision of the basic needs like food, water, oxygen, power, etc., but also environmental needs such as recycling of waste, control of bacteria, and dealing with injuries and illness. Particularly for missions of long duration such as the postulated trip to Mars, the physiological and psychological health of space travellers living in cramped and very isolated conditions will be critical for the success of such a mission just as much as technical issues.

Modern research has shown that human stress can have a significant effect on functional performance and physical health. Stress factors of any nature, be it social, emotional, metabolic, physical or environmental, are regulated through a network of auto-, para- and endocrine messengers. Stress can, for example, lead to a degradation of the immune system performance and potentially contribute a risk to the health and well being of space travellers. Controlled studies of stress have been carried out on board the ISS, as well as under standardised conditions on Earth. These include stress factors like immobilisation, confinement and isolation (e.g. MARS500) together with impacting environmental factors such as hypoxia. The results are comparable to those of sick patients suffering from extreme health conditions under intensive care with long term immobilisation, isolation and hypoxia due to severe disease.

Further research in the next decade will lead to a considerably deeper understanding of the interaction of epigenetics and the environment, that is to say which factors determine the optimal adaption to a stressor, either environmental such as micro-gravity or a disease state. It is known that the epigenetic factors – that is factors that are controlling protein syntheses NOT at the genomic level – seem to be involved in adaptability. Knowing how these mechanisms are controlled will allow individualised therapy as well as allow relevant factors to be used during the selection process for candidates for long space missions (Choukèr 2012).

Technology Area	Tech Level	Development Horizon	Interest
Human stress factors	Level A	long term	robust interest

Entry point: Alexander Choukèr (LMU Hospital, Munich)

9.3 Torpor and hibernation

Artificial hibernation for space travellers is still in the realm of science fiction, but it would be a truly game-changing technology for long space missions. The artificial induction of hypometabolism in cells and organs has been shown to reduce ischemia damage and holds promise for the clinical treatment of stroke and heart attack, for example. However, the idea that humans can be brought to a deep hypometabolic state analogous to hibernation is still hypothetical.

Some mammals can enter a severe hypothermic state during hibernation in which metabolic activity is extremely low, and yet attain full viability when the animal is awake. Although the basic mechanisms underlying hibernation are not well understood, the beneficial effect of hypothermia is well established clinically. However, severe hypothermia induced by clinical drugs is extremely difficult and has been associated with a dramatic increase of cardiac arrest. Nevertheless, the recent discovery of an enzyme which allows non-hibernating mammals to rapidly and safely enter severe hypothermia could remove this risk and lead to use of hypothermia as a routine clinical tool and, potentially, also of application to long space voyages [see Lee (2008) as well as Li et al. (2012)purportedly resulting in a state of \"suspended animation.\" Volatile anesthetics also depress mitochondrial function, an effect that may contribute to their anesthetic properties. In this study, we ask whether H(2 and Szabó (2007)].

Technology Area	Tech Level	Development Horizon	Interest
Torpor and hibernation research	Level A	long term	niche area

Entry point: Alexander Choukèr (LMU Hospital, Munich)

9.4 Nanomedicine

Nanomedicine encompasses all the uses of nanotechnology for the medical domain, including drug delivery, disease treatment and biosensors. Sensing applications were mentioned in a previous section. This section will concentrate on the treatment possibilities offered by the use of nanomaterials.

Nanomaterials have significantly advanced the field of cancer research and, as a result, numerous companies are working on nano-enhanced drugs and treatments [the reported numbers from a review are ~200 companies and ~160 SMEs worldwide, although the report is a bit dated (Wagner et al. 2006)]. The bulk of the applications use nanomaterials as drug carriers for therapeutic applications or as contrast agents for diagnostic imaging. Several drugs have already passed clinical trials and are approved in the USA for human use [see table 1 of Kim, Rutka and Chan (2010) for numerous examples].

In the review of the field of nanomedicine, Wagner et al. (2006) catalogue numerous applications that are already on the market (table 2 of aforementioned report). Some highlights that might be relevant to issues associated with human space flight:

- Drug delivery for multiple sclerosis: Copaxone, a drug consisting of copolymer of alanine, lysine, glutamic acid and tyrosine made by TEVA Pharmaceuticals (Petach Tikva, Israel)
- Emend, nanocrystalline aprepitant antiemetic made by Elan Drug Delivery (Pennsylvania, USA)
- Ostim and Perossal, biomaterials for treatment of bone defects, based on nano-hydroxyapatite, created by Osartis (Obernburg, Germany) and aap Implantate (Berlin, Germany).
- Silver nanoparticles for antimicrobial wound care. The product is named Anticoat and is made by Nucryst (USA)
- Bio-Gate, a German company specialising in antimicrobial agents (silver nanoparticles) and plasma coating techniques for clean instruments and surfaces.

The toxicity of nanomaterials is a significant issue and considerable efforts from government agencies and private enterprises are being made for the documentation of the problem and the creation of standards for the use of nanomaterials in medicine. In Europe, the bulk of nanomedicine research and product development is being conducted by German companies.

Technology Area	Tech Level	Development Horizon	Interest
Nanomedicine (treatment)	Level A-D depending on the issue	medium term	hot topic

Entry point: Alexander Choukèr (LMU Hospital, Munich)

9.5 Synthetic life

The first self replicating synthetic bacterial cell was announced in May 2010, after one and a half decades of work and a 40 M USD investment. The artificially created cell was the Mycoplasma mycoides JCVI-syn1.0 (also named SYNTHIA) (Gibson et al. 2010). Its genome started from digitised genome sequence information and its transplantation into a M. capricolum recipient cell to create new M. mycoides cells that were controlled only by the synthetic chromosome. The work was completed in the Craig Venter Institute, who was also the principal scientist behind the creation of the first synthetic virus, in 2003. According to its creator, "*SYNTHIA was probably the first living creature on Earth whose parent is a computer*".

Synthetic biology is the design and construction of new biological entities, such as enzymes, genetic circuits and cells, or the redesign of existing biological systems. Such changes exceed those introduced previously into biological systems by methods of classic molecular engineering (Wimmer et al. 2009). There has been significant work in the field as the idea of developing useful biological systems (systems that can produce materials that can have industrial applications) hold significant promise for many fields, from pharmaceutical research and biotechnology, to food production, biofuels and biosensors. The global industry analysts Inc[20] report October 2011 mentions that the global synthetic biology market would soon (in 2015) reach above 4.5 billion $.

One potentially interesting application is the use of synthetic microbial factories for production of useful compounds. Not surprisingly, the ultimate goal is the production of biofuels [see, for example, the review from Georgianna and Mayfield (2012) on algae biofuels], with researchers aiming for production of bacteria that can produce liquid fuel from CO_2, sunlight and water. Nevertheless, once the technique of synthesising specific microbes has been mastered, many possible avenues would be possible, such as the creation of antibiotics, biopolymers, amino acids and other compounds that have uses in various industries.

The most obvious application in the context of space is the utilisation of synthetic microorganisms in the Life Support System loop. The engineered microorganisms can be used to consume by-products of the LSS, which were created with other methods, in order to produce useful compounds. As an example, an engineered microorganism has been produced that used methanol as its carbon source (Krog et al. 2013) (this research part has serious industrial applications, as it enables the synthetic biology industry to avoid competing with more traditional biotechnologies for the common raw materials for bacterial growth. Almost no 'normal' bacteria utilise methanol as a food source). This can perhaps be coupled in the future with the significant efforts of scrubbing CO_2 from air, a procedure that has methanol as by-product (Olah, Goeppert and Prakash 2009).

There are other applications that might be possible with mastery of synthetic life. Clinical efforts include the development of synthetic biology therapies for the treatment of infectious diseases and cancer, as well as approaches in vaccine development, cell therapy, and regenerative medicine (Ruder, Lu and Collins 2011). Synthetic viruses might be able one day to combat various infections or suppress harmful bacterial growths (Wimmer et al. 2009). Synthetic cell biosensors might be a good alternative to enzyme-based biosensors since they offer the benefits of low cost and improved stability (Park, Tsai and Chen 2013). Finally, consumables and food for the crew might be created, using the resources available in the various bodies visited by astronauts (Montague et al. 2012).

In the more distant future, it might be possible to synthesise complex artificial life forms, which will probably be non carbon based. These could be used to gain understanding of mechanisms of evolution of simple self-replicating systems that can operate under conditions not encountered in the Earth's biosphere. One interesting aspect of this research is the creation of self propelled synthetic molecules and nanomotors that can move in fluid environments, utilising the ambient chemical energy for locomotion, much like biological systems. Cooperative nanomotors might enable the transportation of 'cargo', either for drug delivery in the human system, or extraction of useful chemicals from the environment (Kapral 2013) [see, for example, Martel et al. (2009) for such an application in surgery].

This research field is still in its infancy and there is a considerable ethical debate on the topic. Due to its nature, the public perception of and response to 'synthetic life' is considered to be amongst the grand challenges the field faces in its future (Porcar et al. 2011).

Technology Area	Tech Level	Development Horizon	Interest
Synthetic life	Level A	long term	robust interest

Entry point: Trygve Brautaset (SINTEF, Norway), Lee Cronin (University of Glasgow)

9.6 Conclusion

This chapter focused on biomedical and medical advancements that could be relative to the space industry and, particularly, human space flight. Most of the development, as expected, is focused on diagnostics, monitoring and treatment. All three areas are of a significant size, since health care is one of the most important aspects in human society.

Novel sensing technologies will be developed with single molecule resolution, for *in vitro* and later also for *in vivo* applications. These developments require joint innovations in physical detection methods, designs of molecular surface architectures, and total system integration. Universities will be prominent if they are able to generate high quality multidisciplinary institutions of sufficient size and with a clear focus in the research, bringing together experimentalists, materials scientists, fabrication experts, theorists and industrial researchers around central research themes.

In the field of modern treatment techniques with novel nano- or nano-assisted drugs, there is signifi-

20. http://www.strategyr.com/default.asp

cant effort to develop therapies for various illnesses, with cancer being the main focus. Nevertheless, the toxicity of the nanoparticles is an open issue and until the issue is settled, nano-medicines will not be widely adopted.

9.7 Section references

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10. Conclusions

As indicated already, this report was prepared to inform on and flag up the main developments in various technological and scientific areas outside 'space' that might hold promise for use in the space domain. However, given the very large number of various non-space technologies identified throughout the TECHBREAK report, the very diverse needs and challenges of ESA and the complex landscape of research and development within the EU, any attempt to prioritise specific technologies for future development would be beyond the scope of this foresight exercise. Nevertheless, at the end of the TECHBREAK process, a possible approach for making use of the European KETs has been proposed in this document.

Some of the technological areas identified in the report involve a large number of actors and are considered 'hot topics' within the European Research Area. It is therefore expected that significant developments and potential breakthroughs will be realised. The TECHBREAK Scientific Committee and experts involved in the project feel that it would critical for ESA to find a way of staying informed of the developments in those fields, developing communication channels with the related communities, and further identifying and expanding the potential use of these technologies. Thus, when the appropriate time comes and the technological development has reached the level where the agency might benefit from it, the appropriate partners would already have been identified and the technology could be spun in the space sector. Possible ways of achieving this would be for ESA to join the European Technology Platforms that might exist on these technologies and identify a way of following the developments in the field. Moreover, ESA might fund or join in specific development programmes. The consultations led during the TECHBREAK project have led us to believe that this approach would be welcomed by those communities.

For those technologies that seem to gather a healthy interest in these communities, albeit without any expectation of immediate progress, it might be better for ESA to take a more leading role in their development, in order to steer the direction towards a predetermined goal. It is suggested that the needs of the agency are prioritised based on this report, and commonalities identified within the KETs. In the case where a given technology would prove significantly promising, the previous steps might be also followed.

Niche areas pose an interesting problem. The promise of a breakthrough is high within some of these technologies but, unless significant funding is gathered, the maturation of the technologies will probably not happen or will be rather slow. Unless there is a significant need to draw on these technologies, funding and effort would probably be spent in other areas, at least in the shorter term.

The discussion concerning the identification of space-specific problems and solutions led us to focus the discussion around the concept of 'Overwhelming Drivers' for space research and exploration. The five 'Overwhelming Drivers for Space' represent the main areas where technological improvements are needed in order to be able to generate breakthroughs in space capabilities. The drivers also served as a brief introduction to the space environment and space operations for the non-space experts and acted as a stimulant for the identification of potential helpful technologies, therefore bridging the knowledge gap between space and non-space experts. Their definition and utilisation aimed at providing the 'food for thought' stimulus that might

Table 19. Technological areas identified in the TECHBREAK process which receive significant attention and funding ('hot' topics). The topics are arranged by technology readiness level. The description of the technologies can be found in their respective sections.

Hot Topics - Technology Areas	Tech Level	Development Horizon	Section
2D materials	Level A	long term	6.2
Fast randomly addressable reconfigurable metamaterials	Level A	medium term	7.5.4
Plasmonic enhanced photosensitivity	Level A	medium term	7.5.8
3D printing	Level A-B	short term	6.10
Nanostructured surfaces	Level B	short term	5.4
Surface plasmon resonance: biosensing	Level B	short term	5.2
CNTs	Level B	medium term	6.6
Organic photovoltaics	Level B	medium term	8.3
Biological and environmental sensors	Level B	short term	9.1
Transparent electrodes	Level B	short term	6.8
Flexible electronics	Level B	medium term	8.6
Smart networks	Level B	short term	8.8
Photonics on chip	Level C	short term	7.1
STT-RAM	Level C	short term	8.1
OLEDs	Level C	medium term	8.2
3D silicon	Level D	short term	8.5
Fully depleted SOI (FD-SOI)	Level D	short term	8.4
Nanomedicine (treatment)	Level B-D	medium term	9.4

Table 20. Technologies that are considered niche research areas, which nevertheless have significant theoretical potential for space applications.

Technology Area	Tech Level	Development Horizon	Section
Boron nitride NTs: structural materials	Level A	long term	6.7
Ferromagnetic and superconducting materials	Level A	long term	6.4
Cryoelectronics	Level A	long term	8.7
Torpor and hibernation research	Level A	long term	9.3

result in a spin-in idea, from a KET field into the space domain. And beyond this goal, it is believed that these five Overwhelming Drivers could also be used throughout ESA's Directorates as a novel categorisation of programme concepts and useful red thread to guide the reflexion about future missions and related technological maturation.

Appendices

Appendix A: **TECHBREAK interviewees**

This section provides the contact details of the European experts who have been interviewed by or provided information to the TECHBREAK committee, regarding promising technologies for utilisation in space. These experts are the 'entry points', identified in the technologies sections and can serve as contacts for ESA within their respective communities.

Brigitte Attal-Tretout
Research Director, ONERA,
Department of physics and instrumentation
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Research Interests: Activities are mainly in materials, lasers metrology and plasma for propulsion. Topics of evaporation of nanoparticles for laser synthesis, material ablation. Catalysis. Laboratory for study of microstructures with the objective to elucidate the thermal gradients problems, vapour-liquid-solid mix (VLS), creation of nano-tubes on the surface of liquids in fusion. Gas diagnosis, laser induced incandescence. Black and white graphene. Main applications in light sensors and gas sensors as well as lightning issues.

Michal Basista
KMM-VIN CEO
michal.basista@kmm-vin.be

Research Interests: Advanced structural materials processing and modelling. In particular, analytical and numerical modelling of effective properties, damage and fracture processes in metal-matrix, ceramic-matrix and infiltrated composites based on micro-CT imaging of real materials microstructure. Processing of MMCs and FGMs using powder metallurgy methods and infiltration techniques.

Chris Bowen
Professor in Materials Science and Engineering, University of Bath, Mechanical Engineering Department
C.R.Bowen@bath.ac.uk

Research Interests: Sensor and actuator materials, Multifunctional ceramics and composites, Structural and functional ceramics, Nanoporous and nanostructured materials, Dielectric properties of materials, Embedded actuators and sensors.

Trygve Brautaset
Research Director, SINTEF
Trygve.Brautaset@sintef.no

Research Interests: SINTEF Materials and Chemistry is a research institute offering high competence within materials technology, applied chemistry and applied biology. SINTEF Materials and Chemistry has facilities in Trondheim and Oslo, Norway. Main interests: Biotechnology, synthetic life and nanomedicine.

Andreas J. Brunner
Swiss Federal Laboratories for Material Testing & Research
Andreas.Brunner@empa.ch

Research Interests: Nondestructive testing of polymers and composites, Fracture Mechanics of fibre-reinforced composites, Mechanical testing of polymers, composites and of parts made of these materials.

Bernhard Brunner
Fraunhofer ISC
bernhard.brunner@isc.fraunhofer.de

Research Interests: innovative non-metallic materials as hybrid inorganic-organic materials (ORMOCER®s), ceramics and glass, Piezoceramics, electroactive polymers, CNTs.

Jose Capmany
VLC Photonics, Chief Innovation Officer
jcapmany@iteam.upv.es

Research Interests: Microwave Photonics, Photonic Integrated Circuit Design, Optical Chip Design, manufacturing and testing.

Thierry Chantraine
Centre Spatial de Liège (CSL)
thierry.chantraine@ulg.ac.be

Research Interests: CSL develops, assembles, calibrates and/or tests unique instruments and systems capable of operating in the harsh environment of deep space.

Alexander Choukèr
Klinikum der Universität München
alexander.chouker@med.uni-muenchen.de

Research Interests: Stress factors (social/emotional/metabolic/physical/environmental), controlled studies for stress research in space (ISS) and under standardised Earth bound conditions either of bed rest (indicating immobilisation stress) or confinement and isolation (e.g. MARS500) with impacting environmental factors.

Appendix A: **TECHBREAK interviewees**

Lee Cronin
Regius Chair of Chemistry, Cronin Laboratory, School of Chemistry, University of Glasgow
lee.cronin@glasgow.ac.uk

Research Interests: self-assembly and self-organisation in chemistry to develop functional molecular and nano-molecular chemical systems; linking architectural design with function and recently engineering system-level functions (e.g., coupled catalytic self-assembly, emergence of inorganic materials and fabrication of inorganic cells that allow complex cooperative behaviours).

Daniel Dolfi
Director of Physics Department at Thales Research and Technology
daniel.dolfi@thalesgroup.com

Research Interests: optoelectronics, lasers, power lasers, supra-conductor components, carbon materials, graphene.

John Errington
Reader of Metalorganic Chemistry, Newcastle University
john.errington@ncl.ac.uk

Research Interests: My interests lie at the interface between molecular solution chemistry and the solid state chemistry of oxide materials. As a consequence, our work centres around a wide range of metal complexes in which the metal is bonded to oxygen donor ligands, particularly metal alkoxides and their derivatives.

Albert Fert
Scientific director, Université Paris-Sud 11 (2007 physics Nobel prize winner)
albert.fert@thalesgroup.com

Research Interests: spintronics and giant magneto-resistance (application to hard disk since 1997). Development of logical circuits based on graphene and spin currents: graphene conserves the spin on long distances without relaxation (more than 100 microns). Work also on magnetic junctions.

Yves Guldner
Director, École Normale Supérieure, Paris
yves.guldner@ens.fr

Research Interests: Nanosciences in general and in condensed matter physics, mostly semiconductors, carbon nano-tube structures, graphene, nano electronics, nano photonics.

Serge Habraken
University of Liège, Physics Department
shabraken@ulg.ac.be

Research Interests: diffractive optics, holography and the fabrication of micro-optics, plasmonics.

Christian Hamm
Alfred Wegener Institute
christian.hamm@awi.de

Research Interests: Evolution and optimisation of technical lightweight structures, mechanical performance of planktonic lightweight structures and their evolution.

Pierre Kern
Research Director at IPAG
pierre.kern@obs.ujf-grenoble.fr

Research Interests: imaging in astronomy in the IR and sub-mm plus other detection innovations such as reshaping optics and focal planes with curves on detectors. Simplification of instrumentation in interferometry.

Lionel Kimerling
Director, Center of MicroPhotonics, MIT
lckim@MIT.EDU

Research Interests: micro-photonics and micro-electronics.

Michèle Lavagna
Associate Professor, Polytechnic Institute of Milan, Department of Aerospace Engineering
lavagna@aero.polimi.it

Research Interests: Orbital mechanics, space systems design, flight and attitude dynamics, optimisation techniques, autonomous spacecraft.

Jean-Yves Marzin
Director of CNRS-INSIS
jean-yves.marzin@lpn.cnrs.fr

Research Interests: Optics of semiconductors, nanostructures of semiconductors. Since 2000, in charge of restructuring research in the domain of nanotechnologies at the ANR (Agence Nationale pour la Recherche) in France. Represents France in COST.

Bruno Mourey
Director of Optics and photonics department at CEA-LETI
Bruno.mourey@cea.fr

Research Interests: optics and components for photon and electron imaging. Activities relate to electro-optics, micro-lighting, lighting, high bit rate transmission on silicon.

Appendix A: **TECHBREAK interviewees**

André Preumont
Université Libre de Bruxelles,
apreumont@ulb.ac.be

Research Interests: Active control of structures with particular attention to large space structures and telescopes. Active vibration control in all fields of engineering, with a particular attention to precision structures.

Menno Prins
Technische Universiteit Eindhoven,
Philips Research, High Tech Campus
menno.prins@philips.com

Research interests: biomedical sensors based on molecular interactions, miniaturised and integrated biosensing systems with single-molecule resolution.

Mikael Rigdahl
Professor, Polymeric Materials and Composites, Materials and Manufacturing Technology , Chalmers University
mikael.rigdahl@chalmers.se

Research Interests: rheology of solids and fluids, composite materials (incl. nanocomposites), renewable materials and the relations between material properties and how we perceive them, e. visually.

Herman Schoo
TNO-Holst Centre, High-Tech Campus 31
herman.schoo@tno.ml

Research Interests: generic technologies for wireless autonomous sensor technologies, organic semiconductors and flexible electronics.

Marie-Noëlle Semeria
Scientific Director at CEA
marie-noelle.semeria@cea.fr

Research Interests: micro and nano technologies development and applications.

Daniel Vellou
Scientific Director, CEA
Daniel.vellou@cea.fr

Research Interests: Innovative applications of micro-nano technologies. Covers all applications but more recently he has focused on medical applications.

William Wadsworth
Centre for Photonics and Photonic Materials, University of Bath
w.j.wadsworth@bath.ac.uk

Research Interests: PCF transitions: inflation, nonlinear optics and interfacing, Fibre sources of single- and pair-photons, PCF design and fabrication, Fibre lasers.

Nikolay Zheludev
Deputy Director of the Optoelectronics Research Centre at Southampton University, Director of Centre for Disruptive Photonic Technologies, Nanyang Technological University, Singapore
niz@orc.soton.ac.uk

Research Interests: nanophotonics, metamaterials and plasmonics.

Appendix B: **Technologies arranged by community interest**

This section gathers all the technologies from the technology chapters of the report. The topics are arranged based on the KETs that they belong to. The tables are ordered based on the community interest for each technology.

Nanotechnology

Technology Area	Tech Level	Development Horizon	Interest	Use	OD
Nanostructured surfaces	Level B	short term	hot topic	bacterial/microbial control	OD5.7
Surface plasmon resonance: biosensing	Level B	short term	hot topic	sampling, health monitoring	OD5.2, OD5.5
Photothermal modulation	Level A	long term	niche area	structure monitoring	OD2.6
Cavity optomechanics	Level A	medium term	robust interest	cryogenics, detectors	OD3.8, OD3.9
Nanoantennas as IR emitters	Level A	long term	robust interest	thermal management	OD2.1, OD2.2
Nanoantennas for detectors/ sensors	Level A	long term	robust interest	optics, detectors, spectroscopy	OD3.8, OD3.9, OD3.10
Nanoparticles for water purification	Level A	long term	robust interest	life support	OD5.9
Nanophononic-enhanced materials	Level A	long term	robust interest	thermal insulators, conductors, thermoelectrics	OD2.1, OD2.2
Surface plasmon resonance: radiation monitoring	Level A	medium term	robust interest	thermal monitoring	OD3.8

Appendix B: **Technologies arranged by community interest**

Advanced Materials

Technology Area	Tech Level	Development Horizon	Interest	Use	OD
2D materials	Level A	long term	hot topic	sensors, detectors, nanomedicine, anti-bacterial treatments, solar cells	OD3.9, OD5.7, OD5.4
3D printing of circuits	Level B	medium term	hot topic	production of robotic swarm of sensors	OD4.7
3D printing of components	Level B	short term	hot topic	repairs, spares	OD2.5
CNTs	Level B	medium term	hot topic	lightweight materials, drug carriers	OD1.1,
Large scale generative production/ 3D printing	Level A	long term	hot topic	advanced fabrication techniques	OD1.2, OD1.4
Transparent electrodes	Level B	short term	hot topic	solar cells, touch screens	OD3.9, OD2.8
3D printing of lenses	Level A	long term	niche area	production of robotic swarm of sensors	OD4.7
Boron nitride NTs: drug delivery	Level A	long term	niche area	drug delivery	OD5.4
Boron nitride NTs: hydrogen storage	Level A	long term	niche area	hydrogen storage	OD2.7
Boron nitride NTs: structural materials	Level A	long term	niche area	new structural material	OD1.1
Ferromagnetic and superconducting materials	Level A	long term	niche area	detectors	OD3.9
Nanoenergetic materials	Level C	medium term	niche area	efficient propulsion	OD1.8
3D printing of fuel cells	Level B	medium term	robust interest	efficient batteries/ fuel cells	OD1.8, OD2.8
3D printing of molecules	Level A	short term	robust interest	chemical and pharmaceutical synthesis	OD5.4
Active control of structures	Level A	medium term	robust interest	reduce mass, maintain stiffness, control of large mirrors	OD1.2, OD3.5
Advanced construction materials	Level A	medium term	robust interest	new lightweight, durable materials	OD1.1, OD1.8, OD2.1, OD2.2, OD3.7
Biomimetic databases	Level B	short term	robust interest	lightweight structures, robotics, sensors	OD1.2
Biomimetic design	Level B	medium term	robust interest	lightweight structures,	OD1.2, OD4.2
Boron nitride NTs: insulators	Level B	long term	robust interest	thermal protection	OD2.1
Multiscale modelling	Level A	medium term	robust interest	simulations, tests	OD2.6
Topological insulators	Level A	long term	robust interest	optoelectronics, memory devices	OD3.9

Appendix B: **Technologies arranged by community interest**

Photonics and Metamaterials					
Technology Area	**Tech Level**	**Development Horizon**	**Interest**	**Use**	**OD**
Photonics on chip	Level C	short term	hot topic	radiation protection, communications	OD1.4, OD1.6, OD3.8, OD3.9, OD4.3, OD4.6
Fast randomly addressable reconfigurable metamaterials	Level A	medium term	hot topic	communications, sensors and detectors	OD3.9
Plasmonic enhanced photosensitivity	Level A	medium term	hot topic	sensors, detectors	OD3.9
Aerogel photonic component packaging	Level C	medium term	robust interest	thermal protection	OD2.1
Photonic crystal fibres	Level C	medium term	robust interest	sensors, radiation resilience	OD1.3, OD1.6, OD3.9
Photonic lantern	Level B	medium term	robust interest	spectroscopy	OD3.9
Frequency selective surfaces	Level A	medium term	robust interest	antenna design, detectors, sensors	OD3.9, OD4.4
Micro-resonators	Level A	medium term	robust interest	spectroscopy	OD3.9
Pupil remapping interferometer	Level B	medium term	robust interest	inteferometry	OD3.9
Vector vortex coronagraph	Level C	medium term	robust interest	detectors	OD3.9
Frequency selective surfaces	Level A	long term	robust interest	temperature cycling	OD3.9, OD4.4
Infrared metamaterials	Level A	long term	robust interest	temperature cycling	OD2.2
Metasurfaces	Level A	long term	robust interest	sensors	OD3.9
Nanocrystals	Level A	long term	robust interest	sensors	OD3.9
Negative index metamaterials	Level A	long term	robust interest	detectors	OD3.9
Phase change films	Level A	long term	robust interest	radiation protection	OD1.6
Planar reconfigurable lenses	Level A	long term	robust interest	sensors	OD3.9
Plasmonic colour separation	Level A	long term	robust interest	sensors	OD3.9
Sapphire PCFs	Level C	long term	robust interest	thermal management	OD2.1

Appendix B: **Technologies arranged by community interest**

Nano-electronics

Technology Area	Tech Level	Development Horizon	Interest	Use	OD
Flexible electronics	Level B	medium term	hot topic	bio-sensors, stress monitoring	OD5.5
Fully depleted SOI (FD-SOI)	Level D	short term	hot topic	integrated circuits, low power and low cost	OD5.5, OD4.7, OD4.3
Silicium 3d	Level D	short term	hot topic	miniaturisation, performance increase in electronics	OD3.9
Smart networks	Level B	short term	hot topic	robotic swarm	OD4.5
STT-RAM	Level C	short term	hot topic	radiation protection	OD1.7
OLEDs	Level C	medium term	hot topic	illumination	OD5.11
Organic photovoltaics	Level B	medium term	hot topic	solar cells	OD1.1, OD3.1, OD4.7
Cryoelectronics	Level A	long term	niche area	sensors	OD3.9
Biological monitoring systems	Level A	medium term	robust interest	crew monitoring	OD5.5
Truly autonomous agents	Level A	medium term	robust interest	self-healing spacecraft, advanced formation flight, new exploration paradigms	OD2.5, OD3.5, OD4.5, OD4.7

Biotechnology/Medicine

Technology Area	Tech Level	Development Horizon	Interest	Use	OD
Biological and environmental sensors	Level B	short term	hot topic	crew monitoring, blood sampling	OD5.6, OD5.5
Nanomedicine (treatment)	Level D	medium term	hot topic	drug delivery, localised treatments	OD5.4
Torpor and hibernation research	Level A	long term	niche area	long duration flights, emergency for seriously injured crew	OD5.2
Human stress factors	Level A	long term	robust interest	astronaut treatment	OD5.2, OD5.5
Synthetic life	Level A	long term	robust interest	Drug delivery, life support system, food production, biosensors, in situ resource utilisation	OD5.4, OD5.2, OD5.6, OD4.7

Appendix C: **Overwhelming Drivers Mapping**

This section presents the Overwhelming Drivers codes that were used throughout the technology descriptions, as well as technology tables. Each code maps to particular ideal solutions within the OD concept.

Code	OD Potential Solution
OD1.1	Replace materials with new, lighter materials with similar or better performance
OD1.2	New structural/active designs that use less materials
OD1.3	Replace cabling materials with lighter ones
OD1.4	Eliminate cables
OD1.5	'Print' cables on the structure itself
OD1.6	Identify novel materials for shielding
OD1.7	Identify novel techniques for radiation shielding
OD1.8	This is a generic solution that indicates the decrease of system mass due to efficiency gains (improved techniques, new materials, etc.)
OD2.1	Materials that can withstand high temperature/high temperature gradients
OD2.2	Advanced thermal control
OD2.3[OD1.6]	Novel shielding techniques that don't rely on bulk material shielding
OD2.4	Automatic repair of radiation damage. Radiation shielding should be complemented with the ability of repairing the damaged material. Self-healing materials and structures are needed.
OD2.5	Self-healing mechanisms, automated repairs
OD2.6	Modelling and accelerated life tests
OD2.7	The storage of hydrogen is made more efficient. Hydrogen is extremely difficult to store for long periods of time. One solution would be the development of a polymer tank to store hydrogen
OD2.8	Being able to provide energy for a long period of time is a problem that will require not only the capability to prevent/repair degradation for the involved systems (i.e., degradation of solar cells), but will also require advances in the efficiency of existing power production systems in order to reduce weight or size or both
OD3.1	Flexible or foldable mirror and support structure, to circumvent volume restrictions on launch
OD3.2	Formation flying of parts (no support structure). Technologies such as micro-thrusters and laser metrology for fine position control and precise formation flying. Formation flying might be achieved by utilising other forces to maintain position, such as ferromagnetic forces
OD3.3	Robotic systems for the assembly of structures in space
OD3.4	Novel packaging and deployment techniques based on biological organisms
OD3.5	Robotic systems for the maintenance of structures in space
OD3.6	Technologies for maintaining the optical surface quality of large mirrors in space
OD3.7	Advanced coating materials to prevent degradation
OD3.8	Energy sensitive detectors with minimum cooling requirements, particularly in the IR and visible ranges, to enable simple, low spectral resolution 2D imaging
OD3.9	Plasmonic optical systems and astrophotonics instrument concepts to reduce both the mass and size of space instruments
OD3.10	Advanced interferometers of ultra-compact dimensions (nanotechnology)

Appendix C: **Overwhelming Drivers Mapping**

Code	OD Potential Solution
OD4.1	Reduce the mass/compacting of instruments, in order to be able to have more instruments on-board. Similar issue as OD1.1-OD1.5 and OD3.8-OD3.10
OD4.2	Novel 'packaging' techniques to increase utility per volume of instruments
OD4.3	Compact/miniaturised instruments, similar to OD3.8 – OD3.10
OD4.4	Miniaturisation of antennas
OD4.5	Artificial intelligence systems to coordinate the parts
OD4.6	Advanced data transfer system development for communication between segments
OD4.7	Mass fabrication of specialised micro/nano bots
OD5.1	New drugs for radiation treatment or radiation poisoning prevention
OD5.2	Advanced countermeasure drugs, to counteract the effects of weightlessness such as muscle and bone mass reduction
OD5.3	Simulation of gravity by technical means (i.e., centrifuges)
OD5.4	Technologies to manufacture drugs and other chemicals in situ. These drugs can either be a result of novel ways to treat the human body RNA regulation or based in new concepts, inspired from biological processes (bio-mimetics)
OD5.5	Nano sensors for the continual monitoring of bodily functions and the environment that would not impede the crew in their duties
OD5.6	Advanced telemedicine and telesurgery equipment for emergencies
OD5.7	Technologies for control of bacteria, to avoid/eliminate the dangers large bacterial concentrations represent to the astronauts. This could be achieved either by using specially treated surfaces or by using mutated bacterial strains that maintain a healthy bacterial population
OD.5.8	In situ production of nutrition
OD5.9	Life Support systems. Advanced filters and catalysts based on nano-engineering could provide a significant advance in this field
OD5.10	Technologies allowing the manufacture of parts/materials in situ (spares, modifications, servicing) through 3-D printing, chemical synthesis (e.g., POM), etc.

Appendix D: Contact Points for European technology platforms

European Technology Platforms: http://cordis.europa.eu/technology-platforms/individual_en.html

Photonics21

The Photonics21 ETP was established in 2005 to foster cooperation and a common identity in its industry. The platform brings together the leading photonics industries and R&D stakeholders. Its objective is to establish development and deployment of photonics in five key industrial areas: ICT, lighting and display, manufacturing, life sciences and security. These are grouped into five application sectors:

- information and communication;
- industrial production and manufacturing and quality;
- life sciences and health;
- lighting and displays;
- security, metrology and sensors.

Additionally two cross-cutting topics have also been defined:

- design and manufacturing of photonic components and systems, and
- photonics education, training and research infrastructure.

Website

http://www.photonics21.org

Notable publications

1. Vision document (2010): *Photonics – Our Vision for a key enabling technology of Europe* http://www.photonics21.org/download/FinalEditionPhotonics21VisionDocument_InternetVersion.pdf
2. Strategic research agenda (2010): *Lighting the way ahead* http://www.photonics21.org/download/Photonics21StrategicResearchAgenda.pdf
3. Photonics in Europe: Economic Impact http://www.photonics21.org/download/Brosch_Photonics_Europe.pdf
4. Multiannual Strategic Roadmap 2014 -2020 http://www.photonics21.org/download/Brochures/Photonics_Roadmap_final_lowres.pdf

European Technology Platform contact

Markus Wilkens, Secretariat:
secretariat@photonics21.org

Advanced Materials

The Advanced Engineering Materials and Technologies (EuMat) ETP was established in 2006 to bring together industry and important stakeholders in the process of establishing R&D needs and priorities in this area. It brings together participants from different disciplines, industry, public authorities, academic community, consortia from EU projects, financial community and civil community, including users and consumers. At present, seven Working Groups have been established to develop R&D priorities and strategy for the EU. These are:

WG 1: Modelling and Multiscale
Chair: Amaya Igartua (Techniker)

WG 2: Materials for Energy
Chair: John Oakey (Cranfield University)

WG 3: Nanomaterials and Nano-Assembled Materials
Chair: Daniele Pullini (CRF)

WG 4: Knowledge-based Structural and Functional Materials
Chair: Michal Basista (IPPT)

WG 5: Lifecycle, Impacts, Risks
Chair: Aleksandar Jovanovic (Steinbeis R-Tech)

WG 6: Materials for Information and Communication Technologies (ICT)
Chair: Wanda Wolny (MEGGITT)

WG 7: Bio-Materials
Chair: Marco Falzetti (CSM)

Website

http://www.eumat.eu

Notable Publications

1. Strategic research agenda update (SRA) (2012) http://www.eumat.org
2. Roadmap (2006): http://www.eumat.org

European Technology Platform contact

Coordinator: Marco Falzetti, CSM Italy
m.falzetti@c-s-m.it
Secretariat: Michal Basista, KMM-VIN AISBL
Michal.Basista@kmm-vin.eu

Micro- and Nano-electronics

The ENIAC Joint Undertaking (JU) was created in February 2008 in order to implement a Joint Technology Initiative (JTI) on nanoelectronics – a research programme aimed at enhancing the further integration and miniaturisation of devices and increasing their functionalities. The ENIAC JU is set up as a public-private partnership, bringing together the European Commission and European Member and Associated States with AENEAS, the association representing the R&D actors in nanoelectronics (Corporate, SMEs, research institutes and universities) in Europe.

Website

http://www.eniac.eu

Notable Publications

1. Multi-annual strategic plan
   http://www.eniac.eu/web/downloads/documents/masp2010.pdf

European Technology Platform contact

ENIAC JU
Email: eniac@eniac.europa.eu

Nanotechnology

There is no single ETP that deals exclusively with nanotechnology. ENIAC, Photonics, Future Textiles and Clothing (FTC) and Nanotechnologies for Medical Applications (Nanomedicine) mention aspects of nanotechnology in their targets.

In particular the Nanotechnologies for Medical Applications (Nanomedice) ETP was established in 2005 to prevent the lack of coordination between industry and academia – together with the EC – in this fast growing field. Nanomedice addresses the development and innovation needs in nanotechnology for health. It aims to strengthen the competitive, scientific and industrial position of Europe in the area of nanomedicine. The strategic research agenda identifies three main areas for research:

1. nanotechnology-based diagnostics including imaging;
2. targeted drug delivery and release;
3. regenerative medicine.
4. Nanomedicine is in close contact with other ETPs, and in particular, the platform cooperates with the Innovative Medicines Joint Undertaking (IMI), Photonics (Photonics 21), Smart System Integration TP (EpoSS) and Sustainable Chemistry (SusChem).

Website

http://www.etp-nanomedicine.eu

Communications

1. Vision document (2005) 'Vision paper and basis for a strategic research agenda for nanomedicine'
   http://www.etp-nanomedicine.eu/public/press-documents/publications/etp-nanomedicine-visionpaper/at_download/file
2. Strategic research agenda (2006) 'Nanomedicine: nanotechnology for health
   http://www.etp-nanomedicine.eu/public/press-documents/publications/strategic-researchagenda/at_download/file

European Technology Platform contact

Paul Smit, Senior Vice-President, Strategy and Business Development, Philips Healthcare

ETP Office
Sebastian Lange, VDI/VDE Innovation + Technik GmbH
secretariat@etp-nanomedicine.eu

Biotechnology

The ETPs that mention biotechnology as part of their focus are: Future Textiles and Clothing (FTC), European Biofuels Technology Platform (EBTP), Food for Life (Food), Nanotechnologies for Medical Applications (Nanomedicine), Plants for the Future (PLANTS), European Technology Platform for Sustainable Chemistry (SusChem).

White Biotechnology

The European Technology Platform for Sustainable Chemistry (SusChem) was established in 2004 and its strategic research agenda focuses on four sections:

- industrial biotechnologies, focusing on the development and production of novel, innovative products and processes in a cost- and eco-efficient manner, and the discovery and optimisation of strains and biocatalysts;
- materials technology, focusing on materials for mankind's future surroundings, which will be designed to enhance the quality of life, with special attention to the role of nanoscience, and the related nanotechnologies;
- reaction and process design, focusing on the identification, design and development of appropriate products and processes that will help achieve them;
- horizontal issues, focusing on ensuring that EU citizens benefit from the development and use of innovations based on the SusChem SRA by addressing environmental, health and societal concerns associated with new products and processes; and stimulating support for innovation.

Website

http://www.suschem.org

Communications

1. Vision document (2005) 'The vision for 2025 and beyond'
   http://www.suschem.org/content.php?_document[ID]=2049&pageId=3599
2. Strategic research agenda (2005)
   http://www.suschem.org/content.php?_document[ID]=2049&pageId=3599
3. Implementation action plan(2006)
   http://www.suschem.org/content.php?_document[ID]=2049&pageId=3599

European Technology Platform contact

Ger Spork
suschem@suschem.org

Information and Communication Technologies

The ETPs mainly dealing with the ICTs are: Mobile and Wireless Communications Technology Platform (eMobility), European Platform on Smart Systems Integration (EPoSS), Networked and Electronic Media (NEM), Networked European Software and Services Initiative (NESSI). Other platforms closely relates with ICTs are Advanced Research and Technology for Embedded Intelligence and Systems (ARTEMIS) and European Technology Platform on Robotics (EUROP).

Mobile and Wireless Communications Technology Platform (eMobility)

The platform was established in 2004 and aims at strengthening research and development in telecommunications systems.

Website

http://www.emobility.eu.org

Communications

1. Strategic Research Agenda, Revision 7 (2008)
   http://www.emobility.eu.org/SRA/eMobility_SRA_07_090115.pdf
2. Strategic Applications Research Agenda, Version 1 (2008)
   http://www.emobility.eu.org/SAA/Strategic_Applications_Agenda_v1-0.pdf

European Technology Platform contact

Fiona Williams
fiona.williams@ericsson.com

European Platform on Smart Systems Integration (EPoSS)

The platform was established in 2006 and the strategic research agenda of the ETP formulates a shared view of research needs of the smart systems integration sector. The sectors identified as most relevant for smart system applications are: automotive, information and telecommunications, medical technologies, RFID, safety and security, cross-cutting issues.

Website

http://www.smart-systems-integration.org

Communications

1. Vision document (2006): 'Towards a vision of innovative smart systems integration'
   http://www.smart-systems-integration.org/public/documents/ eposs_publications/060516_Vision_Paper_fi nal_mit Deckblatt.pdf
2. Strategic research agenda (2007): 'Implementing the European research area for smart systems technologies'
   http://www.smart-systems-integration.org/public/documents/ eposs_publications/EPoSS_SRA_1_3

3. Strategic Research Agenda (2009)
   http://www.smart-systems-integration.org/public/documents/publications/ EPoSS%20Strategic%20Research%20Agenda%202009.pdf

European Technology Platform contact
Klaus Schymanietz (Chairman), EADS
Wolfgang Gessner (Head of the EPoSS Offi ce) VDI/VDE-IT
contact@smart-systems-integration.org

The Networked and Electronic Media (NEM)

NEM was established in 2005 to bringing together various stakeholders, including broadcasters, telecom operators, manufacturers of professional equipment, manufacturers of consumer electronics, academia and standardisation bodies. It aims to cover existing and new technologies, including broadband, mobile and new media across all ICT sectors, to create a new and exciting era of advanced personalised services.

Website
http://www.nem-initiative.org

Communications
1. Vision document (2007): 'NEM vision 2020'
   http://www.nem-initiative.org/Documents/NEM-V-002.pdf
2. Strategic research agenda (2007)
   http://www.nem-initiative.org/Documents/NEM-SRA-050.pdf
3. NEM strategic research agenda coverage by FP7 — Call 1
   http://www.nem-initiative.org/Documents/NEM-SRA-051.pdf

European Technology Platform contact
Jean-Dominique Meunier (Executive Director)
Jean-Dominique.meunier@thomson.net

The Advanced Research and Technology for Embedded Intelligence and Systems (ARTEMIS)

This ETP was established in 2004 and the strategic research agenda focuses on four application contexts:
- industrial systems; large, complex and safety-critical systems, which embraces automotive, aerospace, manufacturing, and growth areas such as biomedical;
- nomadic environments; enabling portable devices and on-body systems to offer users access to information and services while on the move;
- private spaces; such as homes, cars and offices, offering systems and solutions for improved enjoyment, comfort, well-being and safety;
- public infrastructure; major infrastructure such as airports, cities and highways that embrace large-scale deployment of systems and services that benefit the citizen.

Website
http://www.artemisia-association.eu

Communications
Strategic research agenda (2006),
http://www.artemis-etp.eu

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The European Technology Platform on Robotics (EUROP)

This ETP was established in 2005 and its strategic research agenda identifies six application scenarios: manipulation robots, robotic co-workers, logistics robots, security robots, robots used for exploration or inspection, and edutainment.

Website
http://www.robotics-platform.eu

Communications
1. Vision document EUROP, the European Robotics Platform — Glossy Brochure (2005)
   http://www.robotics-platform.eu/documents.htm
2. Strategic research agenda (2009)
   http://www.robotics-platform.eu/cms/index.php?idcat=8

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Appendix E: **TECHBREAK workshop participants**

This table contains participants to the various TECHBREAK workshops or experts who were contacted during the process (but did not participate in the interviews).

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Appendix E: **TECHBREAK workshop participants**

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Referenced Documents

Due to the large number of cited documents and the diverse subjects of this report, a rather unusual style of citation has been utilised. The citation style will follow the (author date) convention and as a result, the documents will be categorised alphabetically and not by order of appearance. This section contains the full bibliography of this report (alphabetical order, by name of first author). The sections that contain the technology descriptions (sections 5, 6, 7, 8 and 9) will also include a partial bibliography, referencing the articles and reports encountered in the text therein. These section references are contained within the main bibliography below.

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List of Acronyms

ACT	Advanced Concepts Team
AFC	Active Fibre Composite
AGPM	Annular Groove Phase Mask
AWI	Alfred Wegener Institute
BAN	Body Area Networks
BN	Boron Nitride
BNNT	Boron Nitride Nanotube
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CMC	Ceramic Matrix Composite
CMOS	Complementary Metal Oxide Semiconductor
CNT	Carbon Nanotubes
DMLS	Direct Metal Laser Sintering
EBL	Electron Beam Lithography
ECG	Electrocardiography
EES	Epidermal Electronic System
EM	Electromagnetic
ESF	European Science Foundation
ESPI	European Space Policy Institute
ESSC	European Space Sciences Committee
FD-SOI	Fully Depleted Silicon On Insulator
FEA	Finite Element Analysis
FEM	Finite Element Method
FGM	Functional Graded Material
FSS	Frequency Selective Surfaces
FTAP	Future Technologies Advisory Panel
HISPAC	High-Level Science Policy Advisory Committee
HMM	Highly Anisotropic Hyperbolic Metamaterial
HMS	Highly Anisotropic Hyperbolic Metasurfaces
ICT	Information And Communication Technologies
IR	Infra-Red
ISI	(Fraunhofer) Institute For Systems And Innovation Research
ITO	Indium Tin Oxide
IWA	Inner Working Angle
KET	Key Enabling Technology
LENS	Laser Engineered Net Shaping
LHC	Large Hadron Collider
LMC	Life Marker Chip
MAS	Multi-Agent System
MDO	Multidisciplinary Design Optimisation
micro-CT	Microcomputed Tomography
MM	Metamaterial
MMC	Metal Matrix Composite
m-RAM	Magnetoresistive RAM
MRL	Manufacturing Readiness Level
NIM	Negative Index (Media) Metamaterial
NPS	Nuclear Power Sources
OD	Overwhelming Driver
OF	Optical Fibre
OLED	Organic Light-Emitting Diode
OPV	Organic Photovoltaics
PCF	Photonic Crystal Fibre
PDOS	Photonic Density Of States
PSF	Point Spread Function
PZT	Lead Zirconate Titanate
RAM	Random Access Memory
RR	Ring Resonator
SLA	Stereolithography
SLM	Selective Laser Melting
SOI	Silicon On Insulator
SPR	Surface Plasmon Resonance
SST-RAM	Spin Transfer Torque RAM
STM	STMicroelectronics
STT-RAM	Spin Torque Transfer - RAM
SWCNT	Single-Walled Carbon Nanotubes
TCO	Transparent Conducting Oxides
TRL	Technology Readiness Level
TTAS	TECHBREAK Technology Assessment System
VLT	Very Large Telescope

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