SPACE 2030 - RESEARCH TRENDS AS INPUT FOR LONG-TERM PLANNING

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Space missions have relatively long development and operation times. At the same time, space missions generally need to rely on already space-proven technology to keep the overall risk levels for failure acceptably low. New technologies are therefore first introduced in experimental and technology demonstration programmes or science missions before entering commercial spacecraft, leading to a "technology delay" of space hardware, which is directly proportional to the rate of technological change. While attempts are made to increase the opportunities to space-qualify technologies and to substantially shorten the development phases of space missions, it seems that these improvements are outperformed by the rate of technological change, especially for space applications competing with alternative terrestrial solutions in strongly innovation-driven markets (e.g. telecommunication). While some areas of space technology continue to be state of the art, in other areas space seems to be gradually losing terrain. As a consequence, spin-in of technology gets more and more important compared to the so far dominant technology transfer from space technology to terrestrial applications. At the same time, space and space applications are losing the prestige and exceptional status enjoyed since the early days of space activities to become an integral part of our daily life.

It is therefore of increasing importance for long term planning of space activities to try to understand and identify technology trends and their direct and indirect impact on space activities.

Within ESA, the Advanced Concepts Team (ACT) is operating as an internal think-tank, performing research on advanced concepts and technologies that are too immature to be considered for regular programmes. As part of its work and based on the assumption that the conceptual and technological changes of tomorrow are already detectable within the ongoing research at universities and research centres, the ACT tries to derive research trends and major development paths in order to inject them as input for long-term strategies. The present paper presents mechanisms put in place to this purpose within ESA and some selected results, obtained in part internally and in part via the academic research network.

"Prediction is very difficult, especially of the future" Niels Bohr

I. INTRODUCTION

Since its very beginnings, space industry has been considered as a "high-technology" domain. Space exploration and space activities have required advances in as varied scientific fields as chemistry, physics, metallurgy, mathematics and the spectacular efforts thus accomplished allowed to lead not only to new academic disciplines but initiated or jump-started developments that would likely have taken much longer otherwise. As an example, the solar photovoltaic cells were first developed and regularly used in space (first used on the US Vanguard satellite as auxiliary power source to the on-board batteries in 1958) before finding small niche markets outside the space business and then entering the regular electricity field.

Similar to and partly in parallel to the efforts related to developing and building up nuclear technology, some currently widespread services and tools can be traced back to developments needed for these large government financed programmes with a strong defence component. These required an unprecedented need for large computing capacities, new logistics and ways of cooperation on complex projects among a big number of contributors and completely new constraints linked to the characteristics of space: every Watt required and gramme put into orbit count. Among the most widely reported services and tools developed for such programmes, photocopy machines, computers, fuel cells could be mentioned.

As a consequence and triggered by a few well known examples, governments of space faring nations have started putting technology spin-off programmes in place in order to facilitate the transfer of technology developed specifically for space activities but with potential in other areas. As an example, ESA's Technology Transfer Programme has successfully transferred over 200 space technologies to non-space sectors for applications as diverse as cooling suits for a Formula 1 racing team, ground penetrating radar to detect cracks in mine tunnels and several health-care innovations. [1]. As part of this process, these activities have also led to the creation of new start-up companies promoted through ESA's Business Incubator. [2]

Hertzfeld has tried to calculate the economic spin-off benefits of companies that have received NASA R&D in life science. Their value-added benefits totalled over $1.5 billion while the NASA R&D total investment in the 15 examined technologies of $ 64 million was found to stimulate an additional $ 200 million in private R&D. [3]

With the end of very large prestige and defence-driven space programmes, government budgets for space activities have been reduced, leading to fewer technologies leap-frogged via space mission investments and a gradual reduction of the technological advance of space technology with respect to other industry domains. In some areas, the dynamics of specific industries even led to a rate of technological evolution that resulted in an inverse relationship: The organisation and production methods and tools of the aeronautics and car industry and especially the IT sector are good examples. While microprocessor life-cycles were still comparable to those of space missions in the 1970s, they have been reduced to only about a year. At the same time, development times for spacecraft have remained fairly constant. As as consequence, spin-in and especially technology spin-in is becoming increasingly important for the space sector.

As an example of a successful ESA initiative to address this point, the Innovation Triangle Initiative can be mentioned. Though not only focussing on spin-in technology but covering the introduction of disruptive innovation into the European space sector in general, spin-in plays an important part in the overall programme. [4]

High rates of innovation, resulting in shorter product cycles, also require space projects to strive to shorten the development times of space missions. Given some natural limits and the lifetime of spacecraft these also result in a need to anticipate (technical and scientific) evolutions and trends. While nobody can pretend to reliably predict the future and without entering the specific domain of future studies, this paper describes one mechanism within ESA, which tries to shed light on some of these trends with a potential impact on the space sector. Other mechanisms within ESA dedicated to prepare its future are not covered by this paper.

II. METHODOLOGY

It is generally accepted that innovation mechanisms in most sectors are a combination of technology-push and market-pull mechanisms, which complement each other. The monopsony structure of space, with a government monopsonist in its centre makes this dynamic slightly more complicated but the general mechanisms remain the same. [5]

Innovation, especially disruptive innovation further tends to occur at the margins and intersections of disciplines. Good examples can be found during the merger of part of the IT and telecom sectors or the introduction of optics and microtechnology into biology in the pharma industry.

The traditional areas where innovative concepts, methodologies and technologies are first conceived and tested are universities and research centres, under the impulse of young, generally unconstrained researchers. Thus there the "next steps", the next potentially disruptive technology or methodology is more likely to first become visible.

In order to address these points, the Advanced Concepts Team (ACT) of ESA, part of the General Studies Programme and mandated to monitor, perform and foster research on advanced space systems, innovative concepts and working methods, is mainly composed of research fellows who join the team as part of their academic career, bring with them the latest techniques and knowledge on state-of-the-art academic research. They furthermore originate from a broad variety of academic fields and operate as a truly interdisciplinary team. Via its research, the team acts as a cross-departmental pathfinder to explore novel, potentially promising areas for ESA and the space sector. [6]

Following the theory sometimes called the "wisdom of crowds" [7] and the notion that innovation can also be driven by expectation, expectations have the possibility to become self-fulfilling prophesies by generating risk capital to "trendy" research areas and therefore increasing the changes for advances in these areas. Hence, a survey of expectations is a sensible way of probing the future.

To this end, the ACT is reviewing some selected reports by research-funding organisations, large corporations, academia and even technology future betting sites on the internet and Delphic polls in order to derive expectations for future science and technology trends. [8] [9] [10] [11]

Furthermore, every two years, a workshop is organised, which combines presentations of research results of ACT researchers, research done within its university network and research highlights in different disciplines not yet closely related to space activities.

In line with a trend towards more interactive, less static conferences (e.g. SciFoo [12]), in 2008 a new element was added to the workshop; the audience, coming from a wide variety of scientific disciplines was invited to interactively participate in the formulation of the collective expectations of upcoming science and technology trends. Very little constraints were given to participants, who had at their disposal a large board with a timeline where they pinned expectations in form of post-it notes.

Furthermore the workshop panels have been organised around meta-themes including contributions from different disciplines. The workshop has proven to offer a rare occasions for scientists from different disciplines to actually exchange and discuss their research in a neutral environment. During the months prior to the workshop participants were shaping these themes via their collaborative definition and discussions facilitated by an online wiki-tool.

The workshop in 2008 was organised around the following four meta-themes:

- Enabling tomorrows pioneers;
- “Vis Viva” from space;
- Driving evolution, and
- Discovering natural paths.

Each of these were discussed by expert panels after the different presentations and then summarized to provide input into a panel entitled ”Space 2030”.

In addition to their participation to the panel discussions and the contributions to the science and technology expectation timelines, all workshop participants were invited to answer the following two questions:

1. ”What, in your opinion, is the most important technology the European Space Agency should invest in?”
2. ”What, in your opinion, is the most important decision the European Space Agency should take?”

The last panel of the workshop was then attempting to combine these inputs (from the papers, the panels and from the audience) like pieces of a puzzle into a multi-facetted picture of expectations, trends and possible environments. These are of course only showing snapshots of parts of different “pictures”, that then can be used to build upon scenarios against which to test the robustness of different strategies. It seems worth underlining that these visions are of course highly dependent on the type of persons speaking at the workshop, the pre-selections done and the dynamic developing during the discussions.

III. RESULTS

A. Workshop timeline expectations

The participants to the workshop were free to put as many post-its on the timeline - ranging from year 2010 to 2030 - as they wished, and to make any type of prediction, whether they could see an immediate connection to space industry or not.

The answers are naturally biased towards the interests of the people present at the workshop, and reflect inspiration received from the presentations and panel discussions. However, they can be seen as the points that many workshop participants took home with them from the talks and discussions, and can therefore be seen as a chart of expectations and interests of a fairly well-informed group of people consisting of persons working and researching in the space sector, as well as scientists from various fields.

The answers put onto the timeline exercise range from predictions about specific technologies to visions of a future society that would organise “concerts on the Moon”. Many of these predictions relate to human exploration and what could be called “colonisation of space”, specifically the Moon and Mars. This is not surprising *per se*, given that these are part of the plans of all major space agencies, but it is interesting that this aspect of space generates so much interest compared to examples that are much closer to daily life, e.g. telecommunication, global positioning systems or missions that are scientifically equally interesting like unmanned exploration missions of other planets.

Viewed in this context many of the answers can be seen as the development of technologies that would help human colonisation of space. The following paragraphs provide some examples. The wordings proposed by workshop participants have been kept unchanged for authenticity.

Based on the inputs received, in the decade from 2010 to 2020, humans are expected to be gradually "enhanced" via the introduction and implantation of new embedded technologies, and at the same time, robotic technologies are believed to be increasingly pervasive. First signs of this trend are already visible and reported in specialised media, like the increasing use of mental performance and memory enhancing drugs especially in US high schools, the transfer of some of the techniques and tools used in high performance sports and the increasing reliance on electronic assistants. The following list provides a few examples provided by workshop attendees.

2013 implanted biosensors

2015 robotic technologies invade our homes; vibration powered subsystems

2020 robot human environment symbiotic systems available for space missions

2022 organ repair

According to the workshop audience, in the decade from 2020-2030, these robotic technology and human augmentations will allow humans to put feet again onto the moon and to extend the industrial and leisure sphere of humanity into low earth orbit with the options of space hotels as part of real space tourism. Examples put forward are:

2019 Space hotels/space tourism

2020 Wo/man on the moon again

2027 Robotic construction of first base on moon

In this context it is important to note that there was no presentation at the workshop of the current plans of space agencies for lunar or martian exploration missions. While the expectations of the workshop participants with respect to human lunar surface missions are slightly less optimistic than the plans announced by the large space agencies, their expectations on the future of space tourism appear more optimistic than those of space agencies.

At the same time, humans are expected to make substantial advances in the understanding of biological principles and how to use them; partly as translated laws for machine behaviour, partly using organisms themselves in hostile environments. Biology and life sciences therefore occupy a much more prominent role in the list of technologies than could be expected in such a workshop at a space agency. Examples include

2026 Self-replicating machines

2028 Extremophiles in Mars environment

2029 Self-organising robot ecologies

2030 Organisms genetically adapted to other planets

These new "machines" and ways of organising are expected to greatly benefit from parallel advances to be made in computing and miniaturisation. Examples put forward contain:

2029 Commercial quantum computing;
Cell-sized computers

Only sometime beyond the time horizon of the exercise, real human colonisation is expected to start on a large scale according to the participants of the workshop. Examples put forward include:

2030+ Noah's ark on the Moon
First space-born baby
Rock-band gives concert on lunar surface

2100 Beginning of Mars terra-forming

B. Workshop - Recommendations by the audience

To the question to the audience on the "most important technology ESA should invest in", not surprisingly, a relative majority of 30% of all answers were related to access to space, launcher and propulsion technologies. These ranged from recommendations for a break-through propulsion programme to specific technologies, like nuclear electric and nuclear thermal propulsion systems. The second most quoted technologies for ESA to invest in (23%) were energy related, including both, advanced energy systems for space (nuclear and advanced solar technologies) as well as wireless power transmission and the use of space-captured solar energy for terrestrial uses. Artificial intelligence and robotics technologies were quoted by 20% of the answers followed by bio- and nanotechnologies (17%). Interestingly, only one answer was specifically including technologies related to human spaceflight.

To the question on the "most important decision for ESA to take", more than 60% of all answers were related to the following three recommendations:

1. increase research, advanced technology and innovation funding and open space to research in other research domains (26%);

2. change the general approach of space activities towards a high-risk low-cost model (18%);
3. improve the visibility and communication of space activities and their benefit to society (18%).

In decreasing order of times proposed, it was recommended to define and communicate a clear long-term goal and vision of ESA/European space activities (9%), to establish strong links to the EU, watch and compete with the Chinese space programme and decide whether to embark on a human spaceflight programme or focus on robotic missions (6% each). Some original suggestions related to the creation of a European space university and the massive support for space tourism.

C. Workshop panel "Space 2030"

Out of the technological trends, some analysis of societal evolutions and needs and the international context, the space 2030 panel identified three, not mutually exclusive scenarios for the use of space in the long-term:

Scenario 1 Protection and Security

Scenario 2 Outreach and Expansion

Scenario 3 Rational Use

While these scenarios can be described distinctively, the final scenario is expected to be a pondered mix of them.

1. Scenario 1

This scenario is based on a vision in which humans and Earth itself is primarily considered as exposed to a wide range of threats and dangers. Some of these threats have human causes and are Earth bound – environmental/climate change, pollution, nuclear proliferation, some are linked to and even coming from space: NEO's/asteroids, space debris, solar eruptions, militarisation of space. In this scenario space is expected to be used primarily as a means to protect Earth and humans, and to develop an Earth-centred focus with a centripetal move. In such a vision, space activities are expected to focus on

- monitoring systems for climate and environment;
- early warning systems both for military purposes and for natural disasters purposes;
- combination of space systems for the prevention of mitigation of disasters;
- space weather systems; and
- further in the future eventually climate control systems.

The role and place of space activities would therefore be determined by the ability of space to help solving problems and mitigate threats. For all such missions, space activities would be questioned regarding the balance between their benefit and the threat they might represent. Solutions offered by space would be compared to "Earthly" alternatives. Holistic, system-level approaches and the integration of space components to larger, complex systems would gain importance, while flag-ship exploration missions for prestige and pure scientific discoveries would likely loose support.

2. Scenario 2

In this scenario Earth is in a centrifugal move and sees the expansion towards outer space as a way to solve its Earthly problems. Space is seen as an end in itself and as a place to conquer, colonise, and explore, following one of the quotes attributed to Konstantin Tsiolkovsky: "The Earth is the cradle of humanity, but mankind cannot stay in the cradle forever."

In such a scenario, the following space programmes would be more prominent:

- large scale exploration of the Solar System, both automatic and human;
- installation of manned outposts;
- use of extraterrestrial resources;
- solar energy from space, solar power systems, either in orbit or on another bodies; and
- in the longer term, terraforming to create alternatives to Earth (safe-havens in space, terraforming of other planets etc).

Space would be seen as a natural frontier that calls to be explored and used and space missions at this aim would likely receive support. Whether cooperatively or in competition, the prestige of pioneering new areas, discovering new sites and developing new techniques to use space would likely be an important motivation.

Analysing the recommendations as reported in section III B, the workshop participants, not surprisingly, either expect or favour this scenario. The recommendations to increase space research and technology, favour innovation and adopt a high-risk model to space activities demonstrate the outward looking, optimistic vision of space activities.

3. Scenario 3

The third scenario as deduced for space from inputs from the workshop is a scenario in which space has no specific part, neither representing a danger as in scenario 1 nor an opportunity as in scenario 2. It is "just" a tool for policies to be used to create services and businesses. Among these one could mention examples like:

- integrated services using different space and non-space systems, or
- a special application could be space tourism.

In such a scenario, governments are likely to focus their space activities on the utilitarian ones, integrating them as much as possible into larger solutions and using both cooperation and competition tools depending on a case-by-case basis.

While none of these scenarios mention pure space science specifically they all assume that science will continue to be the backbone of (European) space activities. There are some further commonalities of the three scenarii: all of them will require some level of space activities and use of space assets, though with different emphasis.

Furthermore, none of these scenarios are including or assuming radical, disruptive changes but assume relatively smooth and evolutionary changes to occur. There are some technical/scientific fields where breakthroughs would of course fundamentally change the picture: one of these would be a breakthrough in means to access Earth orbit.

D. General trends

While taking into account the restrictions inherent to the approach as outlines in the methodology section of this paper, some general trends in science and technology have been deduced.

Following the last three decades, one can identify a general shift in science publications and science funding from physical sciences towards life sciences. This trend is particularly well visible in the evolution of US science funding (figure 1) but, to a similar extent, also observable in Europe. This has consequences also for the space sector, which covers both, physical and life sciences, but due to its nature its considered much closer to physical science.

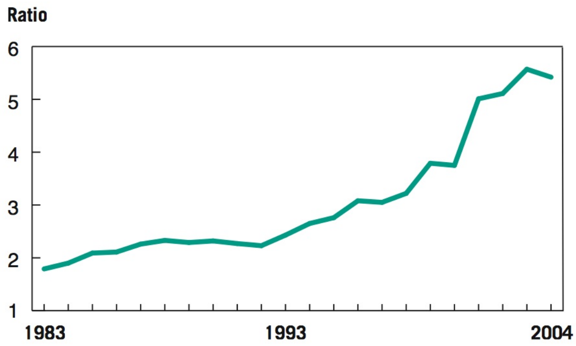

FIG. 1: Ratio of US funding for life sciences to funding for physical sciences. Data: NSF

The brightest students are no longer necessarily choosing physics and engineering disciplines, reducing the basis for talented recruitment in the space sector. With the reduction of governmental space budgets (as example, figure 2 shows the evolution of the budget of NASA in percent of the US federal budget and in total values since 1962) and without the emergence of compensating commercial space activities, the space sector is gradually loosing importance with respect to other science and technology domains.

Moore's law, stipulating an exponential increase in computing performance over time, has been an observed trend for the last four decades. This trend, formulated for the first time in 1965 by Intel co-founder Gordon Moore and based on spectacular and continuous progress in miniaturising of electronic circuits, has been surprisingly solid and enabled not only the emergence of the personal computer industry but revolutionised whole areas of industry and society. [13] Following the predictions as layed out by the International Technology Roadmap for Semiconductors, it is generally expected that the evolution of microchips is likely to continue to progress according to Moore's law for at least until 2020, when most likely fundamental changes to the CMOS chip fabrication technologies will need to be introduced. [14]

For space activities, these have many implications: on the one side, data processing is at the core of space mission. With exponential growth rates in semiconductor chips performance but only little reduction in the development time for spacecraft, the technological discrepancy is increasing between on-board processors and those of terrestrially used ones, e.g. in alternatives solutions to services provided by satellites. Modern software is furthermore integrating new processor capabilities,

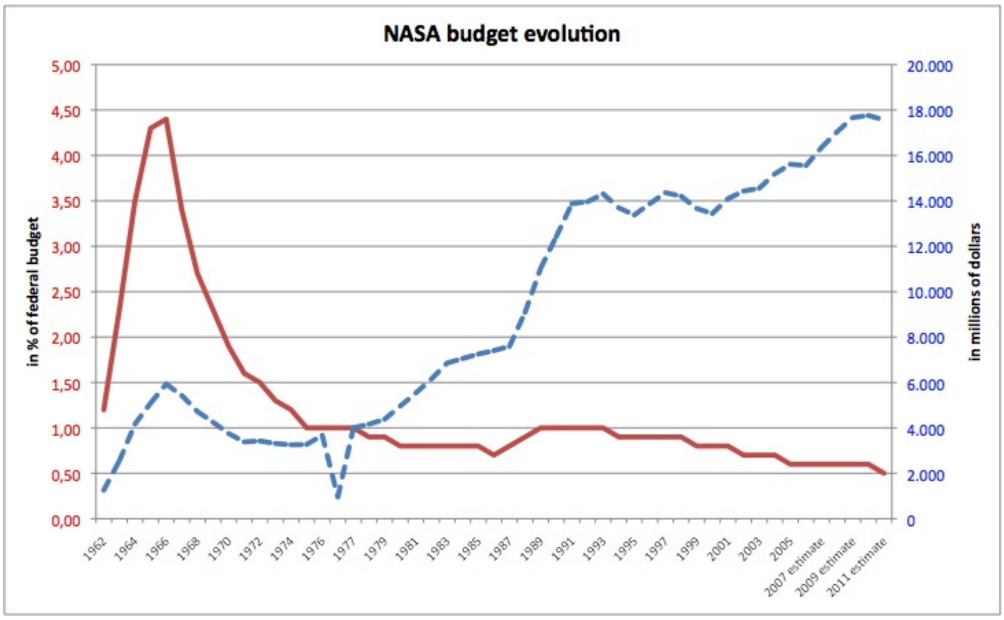

FIG. 2: Evolution of the budget of NASA as percentage of the total US federal budget (left axis, red solid line) and in total M$ values (right axis, blue dotted line); graph compiled from data provided by GOA (`http://www.gpoaccess.gov/usbudget/fy07/hist.html`)

leading to space hard- and software remaining in a small niche of the market and not able to fully benefit from it.

Some general trends were identified both at the workshop and in internal ACT work, for example miniaturisation and the merging of biology and technology. As processors diminish in size and physical interfaces between biological cells and electronic circuits are developed, new possibilities for integrating electronics into organisms (animal and human bodies) or using biological cells as sensors and control systems arise. This trend goes hand in hand with the trend where research money, interest and students move from physical sciences to life sciences and is a leap forward in the progression of IT tools, which are becoming more pervasive and integrated.

Another trend, specific to the space sector and highlighted by participants during the workshop discussions is the result of multi-year budget constraints: the image of space is gradually changing. While space exploration is still able to fascinate the general public, the recent and current large space programmes like e.g. the International Space Station are failing to mark the imagination and generate the enthusiasm in society of the space programmes of the 1960s and 1970s. This results in a negative circle with reduced funding and reduced interest.

While the recent governmental initiatives to counter this evolution, like the presentation of a renewed US vision for space exploration in 2004 and the resulting focussing of NASA's objectives, received surprisingly little attention by workshop participants, the still fairly marginal private initiatives related to space tourism, the emergence of small, frequent and possibly even personalised satellites and space services and a more vague adoption of a general industrial tendency towards increased "user involvement" occupied a much larger share in the discussions of the workshop.

The current state of space activities and the space industry have been compared to the computing industry during the 1970s: created by and via the needs of large governmental programmes with a strong defence component, dominated by a few high-tech enterprises, with a restrictively high entrance barrier (e.g. cost of mainframe computer systems in the 1970s and cost of satellites and access to space) and relatively closed with little input from outside and other domains. The invention of the personal computer, independent software, user-interfaces and the "handing over" of the decisions what to use it for to the users, led to completely new uses and markets: while computers were so far essentially used for large calculations, people started to play games with them in addition to writing letters. The internet, the use by the porno and advertising industry brought further radical changes hardly envisaged by the mainframe computer industry of the 1970s. Could the space sector currently be in a similar situation? Are some of the recent developments (private suborbital spaceflight, attempts to develop fully privately financed launchers, student involvement in micro and nanosatellites, advertisement financed, free earth-observation data via Google Earth, etc) still outside the mainstream space business indicators for larger change?

E. Long-term planning

The identification and understanding of trends that might effect ESA and the space sector constitute only a first step and would remain of "only" academic nature if not used as input to the decision making process. Some of the concrete research outputs of advanced research groups like the ACT can be taken into account into mainstream R&D planning and their advanced methods and techniques can be transferred into the space sector. The less tangible but at least equally important aspect of insight into science and technology trends are on the other hand useful as input at a corporate strategy level, even if most of the time, such information is considered only as a minor contribution to corporate strategies, which are dominated by e.g. economic developments of the main stakeholders (member states as well as space industry in case of ESA), trends in long-term strategic relations (relation ship between ESA and EC, ESA and the defence sector), international perspectives and the development of main partners and competitors to name a few.

In order to be able to be taken into account at a strategic decision level, it is however necessary that advanced research results in science and technology are properly communicated, interpreted and put into a larger context which generally exceed its underlying scientific and technical data.

IV. CONCLUSIONS

Understanding trends in science and technology and interpreting state-of-the-art research results in view of their potential to influence future space activities is an input to long-term strategies. This paper presents some mechanisms adopted by a corporate research think-tank, the Advanced Concepts Team of ESA. These include the analysis of research results of the team and its academic network, the analysis of science and technology forecast reports and interpretation of expectations of the science community as expressed during advanced concepts workshops.

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