Living Technology Artificial Systems Embodied Evolution

FET Consultation Workshop

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Report

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Contents

Executive Summary

Future and Emerging Technologies − Proactive Initiatives (FET − Proactive) is preparing the next work programme for 2013 and later. As part of the process to identify new research challenges, the European Commission organised a workshop on 10 November 2011, in Brussels, to brainstorm and elaborate novel candidates for future FET proactive initiatives in the area of Living Technologies. The meeting was attended by 12 researchers and covered a broad range of topics linked to this theme. The objective was to identify specific topics as suitable candidates for future proactive initiatives.

In discussion following the presentations of the individual participants, the group identified a single broad challenge which they felt captured most of the key components of the individual challenges proposed. This single challenge was then further explored and elaborated as a potential seed theme for a future proactive initiative. The initial description offered here (detailed in Section 3 of this report) takes a first step, but will require further elaboration and refinement.

This report summarises the discussions that took place during the workshop by presenting a list of proposed challenges. Annexes I, II and III of this report give a list of workshop participants, the terms of reference of the meeting and the written contributions of the experts who participated.

1. Introduction

Future Emerging Technologies (FET) Proactive is a part of the Information and Communication Technology (ICT) Programme of the European Commission. FET acts as a pathfinder for the ICTs of the future supporting foundational long-term research and technological innovation and by fostering the emergence of new European research communities in ICT.

FET addresses evolutionary and revolutionary approaches through multidisciplinary cooperation. It explores novel future technology options, identifies new drivers for research, and brings new science into ICTs to expand their scientific foundations. To that aim, it supports radically new and catalytic ideas expected to have a transforming impact on society and technology. FET Proactive structures research in a number of proactive initiatives, which typically consist of a group of projects funded around a common theme. The themes are shaped through interaction with the research community and focus on the mission outlined above.

In this context, the meeting "Living Technologies," held in Brussels on the 10 November 2011, brought together key scientists with diverse expertise to brainstorm and elaborate novel research topics as candidates for FET proactive initiatives with relevance for the FET Work Programme 2013 and beyond. Participants were invited to share their views and work together to identify new key challenges which go beyond traditional lines of research and existing initiatives.

2 Synthesis of the discussions

In short presentations, the attending scientists first detailed 12 different possible themes for future proactive initiatives. This report gives a brief description of each proposed idea below (the initial contributions are included in Appendix III):

2.1 The Challenge of Artificial Evolutionary Ecology with Populations of Artificial Embodied Agents
Nicolas Bredeche, Universite Paris-Sud

Fields such as Evolutionary Robotics, Epigenetic Robotics or Artificial Life recognize a difference between evolution, as driven by an environment, and development, reflecting inherent plasticity linked to an organism's adaptation to prior environments. The interaction between these two levels remains poorly understood in Computer Science and Robotics. An emerging field which focuses on these interactions -- Artificial Evolutionary Ecology -- seeks to understand important collective and individual dynamics in response to environmental pressure, including the emergence of consensus, evolution of cooperative and/or altruistic behaviours, group specialisation and speciation, and so on. A key challenge in Living Technologies is to pursue a deeper understanding, in theory and in practice, of this interaction between longer-term evolutionary dynamics and shorter-term developmental plasticity in the scope of artificial organisms. A key challenge for the future is to achieve such artificial organisms through programmable bio-matter.

2.2 Embodied Artificial Evolution: Inorganic Biology
Lee Cronin, University of Glasgow

There are two promising approaches to embodied artificial evolution -- a top-down approach based on reactor-engineered evolvable matter (RE2M) and a bottom-up approach based on complex inorganic chemistry (iCHELL). The resulting systems would be quite different. RE2M would be a highly sophisticated functional material that would be potentially intelligent but 'dead' (unable to self-sustain or reproduce) whereas iCHELLS would be living inorganic analogues of organic biology. Either technology would bring valuable benefits and applications and each also involves significant conceptual, scientific, technological and ethical issues.

2.3 Challenges in New Living Technologies
Vitor Martins Dos Santos, Wageningen University

In our capacity to understand and harness living technologies we are currently in something like a pre-industrial phase. Our ability to discover new compounds in the space of what is possible, to generate new functions or to re-programme biological behaviour to our benefit is still extremely limited. Synthetic biology with ICT would help us search this space in a much smarter way and to devise strategies for navigating and re-programming cellular behaviour. There are two promising routes to achieving this. Long term, we may first build up biological systems from scratch using simple molecules. In the short term, we may alternatively take living entities such as bacteria and reduce their complexity (streamlining genomes or finding a "minimal" genome) for subsequent computer-driven re-programming through robust genetic compilers, "plug-and-play" circuits and steering of interactions within the microbial chassis. Either case presents challenges as biological components are context dependent, subject to evolution, interact with chemicals and gain their functions through emergent processes. Technological challenges include gaining sufficient understanding of the wiring underlying cellular networks, abstracting the designer from the process of part/function selection and optimization, adapting current protocols for the scope and scale required for synthetic biology, and establishing a critical mass of practitioners.

2.4 Embodied Artificial Evolution
Gusz Eiben, VU Amsterdam

Embodied artificial evolution (EAE) would involve a population of physical (not virtual) units reproducing themselves in the real world with authentic 'birth' and 'death' events. Two possible routes to EAE are 1) inorganic mechatrono-robotic systems or 2) organic, bio-chemical systems. The main challenge is to achieve true reproduction. EAE can lead to solving new design and engineering problems, and solving existing ones in new ways. In fact, EAE technology can be the basis of a transitional change in how design tasks are solved, bringing design and manufacturing together in a continuous process. Once we equip certain groups of artifacts with the ability to evolve, we create the possibility that some of the evolved designs may be truly original, stepping beyond the limits of human thinking. Such systems may also form the basis of a new experimentalism in biology, where evolution can be studied in a radically new way based on controlled experiments in a new medium.

2.5 Living Technology and Artificial Systems
Christian Gamrat, CEA, France

Despite the power of modern ICT, our current computing devices still lack the self-adaptation properties that living organisms exhibit routinely and in an energy efficient way. Nature mastered self-adaptation with a variety of mechanisms which are far beyond the capabilities of our smartest artifacts. To implement artificial systems capable of self-behaviour and evolution, one needs to tackle a multi-parameter, multi disciplinary landscape. We will need to invent new ways to encode and handle information. However we must not disregard the capabilities of current ICT technologies, and should pursue hybrid systems. After all, if current computing circuits are not really intelligent, self-adaptive, self-organizing or cannot do simple things that brains do, they are vastly superior in dealing with mathematical concepts.

2.6 Artificial Living Systems and Embodied Evolution
Serge Kernbach, University of Stuttgart

The outstanding challenge we face is to create truly autonomous, self-supporting, self-replicating and self-sustaining systems. To some extent, understanding life means not only being able to create it from scratch, but also improving, supporting, saving it, or even making it even more advanced. This can be thought of as a long-term goal of living technologies and embodied evolution. The current research agenda targets several short- and middle-term goals: connecting ICT and bio-/chemo-processes, advancing the engineering of "soft" and "wet" robotics, integrating materials science into developmental robotics, and potentially, addressing self-replication in autonomous systems. The most important aspect of all this is developing hybrid technologies by integrating different research fields. This can be done only in large interdisciplinary teams, e.g. within large European projects.

2.7 Sustainable Personal Living Technologies
John McCaskill, University of Bochum and Steen Rasmussen, University of Southern Denmark

Future molecular information processing must provide solutions to real-world embedded problems requiring nanoscale information densities by combining the production of new molecular structures with information processing by existing structures. This is also the key distinguishing feature of living systems. Mastering the combinatorial programming of such systems provides a route to molecular information processing in which computation is linked directly with fabrication. Interfaces can now be developed which can make this technology reproducibly programmable (and hence communicable via the internet). Combined with devices analogous to but extending desktop 3D-printing to include functional device output and parallel self-assembly, this technology could then be made available to individuals for personal molecular-scale fabrication. The challenge outlines a path to a truly sustainable economy, because individuals would be directly responsible for efficient high-tech production, once the recoverability of resource materials in the programmable design is taken into account. It is also a natural development beyond the personal computer.

2.8 Bio-inspiration and Biomimetics
Claudio Rossi, Universidad Politécnica de Madrid

Even the most advanced robots move in extremely clumsy and often dangerous ways, largely due to limitations inherent to their electro-mechanic motor control systems. Giving future robots more complex sensory-motor capabilities will require a radical change in actuation technology and a shift to functional or "smart" materials such as electro-active polymers. Animal muscles are complex structures having smart properties integrated into their design, properties that allow flexible and optimal control of diverse dynamics. We believe that research efforts directed towards mimicking animal muscles with smart materials would be of great interest for the next generation service robots.

2.9 Bio-hybrid Systems
Thomas Schmickl, University Graz

The science of animal-machine interaction at the collective level remains largely unexplored. Yet if intelligent artificial systems (robots, sensor and actuators networks, etc.) could send appropriate cues to animals within a group, such signals might exploit interactions taking place between individuals to steer animal groups toward desired ends. Such technology might be applied in diverse settings, ranging from the agricultural management of farm animals to the control of swarms of termites or locusts. The challenge is to build and explore a basic science and engineering of mixed societies composed of robots and animals together.

2.10 Learning from Life's Principles
Mihaela Ulieru, University of New Brunswick

In the quest to design systems and organizations with high agility, we seek to imitate unique properties of living systems -- their ability to self-organize and adapt, to reconfigure and quickly respond to unexpected environmental demands. Applications for such technology abound in our ever-changing world, especially given the typically rigid structures of our social, political and economic systems. The challenge is to gain an understanding of the mechanisms that make a living technology "alive," and so learn how similar mechanisms might be used to improve our organizations, our socio-politico-economic systems and our overall interaction with the natural environment.

2.11 Living / Non-Living Interfaces
Andy Adamatzky, University of the West of England

We now have tremendous opportunities to build far more sophisticated interfaces linking living and non-living matter. This is due in part to an ever expanding understanding of biology, but also to rapid advances in novel electronics and non-linear chemistry which makes bio-hybrid technologies possible. A key challenge for the future is focusing on implants and implant-like technologies for biomedical applications. Our ultimate goal is to help people and this is a direct way to do so. It is also important to emphasize that far too much attention is typically given to theoretical research over applied work. For every 1000 theory papers we generally see only about one real prototype device. FET challenges should focus strongly on building real prototypes.

2.12 Self-Reproduction and Assembly
Larry Bull, University of the West of England

Unconventional computing and evolutionary computing are being explored in physical systems such as conductive polymers, liquid crystals and in non-linear chemical systems. The use of conductive/electroactive polymers or memristive polymers, along with traditional 3D printing polymers, are also promising. The aim is to create physically instantiated, analogue logic devices exploiting the material properties, size and shape of its substrate, along with the physical size, shape and materials of the rest of the artificial entity. From a computer science perspective, the areas of evolutionary algorithms, self-replication and assembly, and unconventional substrates seem most relevant to the pursuit of technologies which would deserve the name "living."

In subsequent open discussion, participants sought to identify unifying themes or challenges from these 12 proposals. Participants commented on the strong overlap of all the proposed challenges, specifically through core concepts such as living technology, physical embodiment, autonomy of reproduction, and a host of self-* properties such as self-adaptation, self-assembly and so on.

Participants also emphasized their strong desire to move beyond theory and for the challenge to be aimed toward the production of real prototypes. The participants emphasized the need for accompanying research to ensure the safety and control of such technology, depending on the degree of autonomy and self-reproduction, point of deployment, compatability with environmental resources etc. and to evaluate social impact.

Participants decided that their proposals had sufficient unity to be captured within a single, broadly inclusive challenge. Most of the remaining discussion focussed on developing a description of this challenge, and exploring its potential as a focus of future FET programmes. This challenge described in the next section is the result of this discussion.

3 Challenge: Evolving Living Technology

3.1 Challenges / Motivation

Modern ICT technology works through speed and processing power, yet remains primitive in comparison to the computational and self-adapting properties of living organisms. All natural living systems are composed of physically and chemically embodied agents that are relatively autonomous, self-constructing, evolvable and self-organizing. They show a long list of desired features: They are scalable with local communication, reactive (flexible), adaptive and robust against disturbances of many kinds. Learning to build our own ICT along these lines appears to offer the most promising way to solve a host of seemingly insurmountable problems, including software reliability and ease of creation and use, energy supply, difficulty of manufacturing, etc.

Hence, the challenge is to create controllable yet evolving living technologies that co-organize information and matter in collective systems of physical entities. These systems will include an integration of self-assembly and self-reproduction, and have an ability to balance fully open-ended evolution with more constrained and directed evolution, so as to maintain control over outcomes. This will allow us to learn how to exert flexible and useful control over evolving living technologies.

The only living systems we know today are generated by biological evolution. Hence, it is of relevance to anchor our technologies in an understanding of the biological principles of evolution and adaptation. This asks for initiatives where combined empirical, theoretical and synthetic approaches are brought together to address key principles that can drive future living technologies.

Along the way, it will also integrate production and information processing, i.e. overcoming the boundaries between hardware and software, in terms of locality, autonomy and user control, editing, compilation, deployment, evolution and proliferation. This is a crucial challenge that would overcome the key roadblock in current ICT reflected in the separation of software/hardware, and is critical for embedded systems where information processing must be conducted in connection with real-time functional systems, most frequently in massively parallel and nanoscale systems. To achieve this, the computer must become predominantly locally self-programming, ensuring effective function beyond the limits of energy-intensive global communication.

Achieving this will necessarily require the controlled coupling of processes at widely different physical scales, and the creation of interfaces able to link hybrid systems (e.g., evolving artificial self-organizing systems mixed with natural self-organizing systems) with adequate bandwidth to allow crucial information flows. This will allow us to inject control information into these autonomous systems. At the same time, we will also require a systematic reduction in size, timescale and localization of the currently global ICT manufacturing cycle towards closed-loop nanoscale self-production and self-reproduction.

A strong intermediate step towards this, which explicitly and responsibly involves humans in-the-loop, is the target of personal embedded-system ICT fabrication. This is an enabling technology that will require us to deal with many of the issues raised, while maintaining strong human control and engagement, and one that will foster widespread and need-driven use.

However living technologies are realised, it is clear that the development of agents or body types will be required to meet the goal of embedded artificial evolution. The key challenge is the implementation of replication / copying / reproduction as well as the allowance for mutation and variation of the system in interaction with its environment. It will involve physical rather than virtual units undergoing real 'birth' and 'death' events, as well as reproduction and selection.

These challenges need to be demonstrated in real prototypes that take significant steps towards achieving self-reproduction in information processing systems, including properties such as self-healing, on-going self-production, self-assembly, genetically encoded design and self-regulating dynamics.

Finally, we should expect artificial living systems to have a high degree of plasticity and tendency to developmental drift. This may arise from their long-term developmental independence and autonomous behaviour, from the emergence of artificial sociality or other mechanisms of evolutionary self-organization. Such systems will be very flexible and adaptive, and may massively increase their own degrees of freedom. We will hence face new challenges in learning to control such systems over the long-term, ensuring the safe engineering of open-ended evolution and positive impacts on society.

3.2 Suggested Approach / Research Topics

A full understanding of life ultimately entails acquiring the ability to design and produce radically new forms. Since we are living entities ourselves, this of course is never "from scratch" but a measure of our understanding is the degree to which the design and production is independent of living organisms. Of course novelty is not the only objective, but also supporting, preserving and adapting life to deal with new challenges including those induced by technology. Current research distinguishes a number of possible approaches or scenarios for pursuing living technologies and embodied evolution.

First, further development of micro- and nano- mechatronics may make it possible to achieve an advanced functionality (such as self-replication) at the bottom layers without involving chemical reactions. This involves several different technologies from material science, and we can denote this bottom-up scenario as a *nano-mechatronic scenario*. It is inspired by research on artificial self-replicating systems in simulation and physically instantiated, and exploits bio-physical mechanisms.

Second, an alternative bottom up scenario involves orchestrating chemical reactions to produce and deploy new compounds and associations. Nano-mechatronics does not capture the necessary chemical dimension to the problem of coupling construction with function and information processing. A promising approach in this regard would seek the seamless integration of ICT and production by using biological information encoding principles at the molecular level on novel chemical systems. These systems can be bootstrapped and enhanced by electronically programmable local manipulation systems, which also provide an interface with conventional information processing.

Third, the complexity of upper levels (such as information processing) may be transformed through bio-technologies issuing from advances in minimal and streamlined cell projects and cellular programmability. Here we would expect to see the emergence of pure *bio-synthetic systems*.

Fourth, inclusion of the capabilities (sensors, actuation) of naturally evolved life forms into bio-hybrid systems can be used to extend the robustness, flexibility and scalability of the collective systems that emerge from the evolutionary processes shaping those hybrids.

Finally, all of the above approaches may be merged in a way that makes complementary use of their individual advantages. This approach could be called *bio-hybrid*, and would combine bio-chemical and mechatronic autonomous systems. This may be the most promising route for both short- and long-term success.

Research toward living technologies will also benefit from a close consideration of pathways by which alternative top-down and bottom up technologies may ultimately converge in the future. The top down technologies need to become more chemical and embrace more self-assembly, embedded evolution and self-production in increasingly small control loops. The bottom up technologies need to become more programmable and controllable, develop an embodied description of their own construction process and progress further up the integration ladder.

The pursuit of any of these scenarios must also adopt an approach emphasising the integration of methodologies and paradigms from different areas of (synthetic) biology, chemistry, material science and robotics. This new integration will require a deep re-structuring of the current research landscape, changing how we think about (bio)synthetic systems and extending their scientific and technological boundaries.

3.3 Expected Impact

Success on this challenge will cause a profound shift in the direction of future ICT design, engineering and applications. Information will remain at the core of ICT, but will be more tightly integrated with biological and physical processes, and production. There will be endless possibilities for designed autonomous manufacture with a close connection between the place of production and deployment (medicine, agriculture, chemistry, self-correcting computers, etc.).

Indeed, the creation of systems able to live, evolve and reproduce will likely revolutionize all of science and industry, possibly transforming them as much as the first computer revolution. Systems will be adaptive to their environments, fully autonomous, self healing and perhaps able to find their own energy supplies.

Once we equip certain groups of artifacts and (biological) entities with the ability to evolve, we create the possibility that some of the evolved designs will be truly original, stepping out of the limited box defined by human thinking.

Also, these systems can form the basis of a new computer-aided, model-driven experimentalism in biology, where evolution can be studied in a radically new way, based on controlled and repeatable experiments in a new medium. This will enable a deeper understanding of evolution in general.

The idea of bio-hybrid systems, if interpreted in its broadest sense, could also lead to a wide class of further applications in agriculture, forestry and ecology management. Moving up from the micro to macro-scale, it may be possible to integrate artificial organisms into natural living populations so as to achieve an ability to manage such populations for various purposes. These could range from reducing stress in live-stock to the control of animal pests (termites, etc.) by leading them away from specific sites or the artificial support of endangered species. Such technologies might also be used to improve the selectivity of industrial fishing to achieve a more sustainable management.

Lessons from life's processes are priceless in restructuring the organization of our social processes into more fluid and organic structures that enable the manifestation of creativity through social innovation generation. We may learn how to facilitate a transition from current rigid governance structures into more agile, responsive and fluid structures capable of fostering creativity and supporting innovation.

3.4 Suitability for ICT / long term vision

Research and development in ICT currently revolves around information processing, with information considered as an abstract disembodied quantity. This perspective naturally leads to a clear separation between the physical hardware – in which the information is stored and manipulated – and the software which directs the process. This is a specific vision of computation (as originally articulated by John Von Neumann), and its limitations are today reflected in the many things current ICT does poorly or not at all -- responding to errors, reprogramming themselves, adapting to the ever changing demands of their users.

Biological organisms readily handle these challenges and so could artificial devices if they use the same techniques. Hence, this challenge is very clearly relevant to ICT/FET.

Progress on this challenge could revolutionize ICT as we know it by offering an alternative to the von Neumannian architecture and thus redefining the very notions of program, programming, software, software engineering, etc.

Progress may also help to make ICT a core part of the human response to global problems. Personal fabrication of molecular information processing devices and systems could help build a sustainable economy and aid the transition from a mass-production society of inanimate artifacts to a technology-enhanced human society.

3.5 Communities

Progress on this challenge will require the growth and integration of an entirely new cross disciplinary community of researchers drawn from a wide range of existing communities. These include synthetic biology, non-linear chemistry, embodied evolution, self-adaptation (also -reproduction, - assembly, -healing, etc.), evolutionary computing, hybrid systems, robotics, organic or natural design, smart structures, scale coupling and unconventional computing. Progress on this challenge will also have an impact for a much broader range of communities including philosophy, ethics, religion and law.

Annex I : List of Participants

Nicolas Bredeche, Universite Paris-Sud

Lee Cronin, University of Glasgow

Vitor Martins Dos Santos, Wageningen University

Agoston Eiben, VU Amsterdam

Christian Gamrat, CEA

Serge Kernbach, University of Stuttgart

John McCaskill, University of Bochum

Claudio Rossi, Universidad Politécnica de Madrid

Thomas Schmickl, University Graz

Mihaela Ulieru, University of New Brunswick

Andy Adamatzky, University of the West of England

Larry Bull, University of the West of England

Dagmar Floeck, European Commission, DG Information Society & Media, Future and Emerging Technologies

David Guedj, European Commission, DG Information Society & Media, Future and Emerging Technologies

Wolfgang Boch, Head of Unit, European Commission, DG Information Society & Media, Future and Emerging Technologies - Proactive

Mark Buchanan, Nature Physics , Rapporteur

Annex II: Workshop Terms of Reference

Context

FET (Future Emerging Technologies) acts as a pathfinder for the information and communication technology programme of the EU by fostering novel non-conventional approaches, foundational research and supporting initial developments on long-term research and technological innovation. FET structures research in a number of proactive initiatives, which typically consist of a group of projects funded around a common theme. The themes are shaped through interaction with the research community, and focus on novel approaches, foundational research and initial developments on long-term research and technological innovation.

To help identify new research challenges and opportunities for the future, FET has launched a brainstorming process involving interaction with research experts who can help the Commission define new proactive initiatives. The aim is to look beyond traditional lines of research in order to recognise future and emerging areas as well as opportunities for collaboration with other communities. The final results will contribute to establishing the work programme for 2013.

In this context we are launching a consultation entitled "*Living technology/Artificial systems/Embodied evolution*" on the 10 November, 2011 in Brussels. The report resulting from this meeting, will act as a key input to the drafting of future FET proactive initiatives.

Consultation

You are invited to join a select group of researchers active in this field and participate in this consultation. The invitation is sent to you personally in recognition of your research reputation as determined by peers and it is not transferrable. We would hope that you would be willing and able to participate, but please note that you would need to commit to the whole discussion (starting at 9:00 and finishing at 17:00 on 10 Nov) as the collaborative effort and resulting report will emerge during this period. Participants arriving late or leaving early can have a disruptive effect on the consultative process, so being present for the whole meeting is important. Unfortunately, the Commission is not in a position to reimburse travel costs to this meeting.

Short Presentation

To get discussion underway, each participant would be asked to give a five-minute presentation summarising their vision of emerging research. The objective is not to validate existing research but identify topics, challenges and ideas for new proactive initiatives. The series of five-minute "previews" are meant to act as a discussion starting point and participants will have full opportunity for expansion of their ideas in later discussion. The following is suggested as a focus for presentations and discussion.

- **Challenges / new areas** - why are these an opportunity?
- **Research topics –** why and how are these different than existing research

- **Impact** - what potential impact on information processing and communication from a breakthrough in this area ?
- **Suitability for ICT and FET** - what makes this suitable for ICT and FET as opposed to the mainstream programme? Is it vision-driven and high-risk, embryonic or foundational?
- Suitability of the theme beyond ICT
- **Communities** - is this topic addressing an existing or new community?

Short Position Paper

You are also invited to prepare a short (1- 2 page) position paper inspired by some of the issues below, but feel free to address your own preferences:

Living technology/Artificial systems/Embodied Evolution

- What is the ideal mechanism?
- Relation learning – self-organisation – evolution
- Controllability and predictability
- Intelligence/Agents required?
- Process from genotype to phenotype

To prepare for effective discussion, we would appreciate receiving your presentation slides and position paper by 4 November, and these will be collated as a handout for the meeting. These will be treated as draft versions for circulation only to meeting participants.

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FET in the 7th Framework Programme:
http://cordis.europa.eu/fet