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Table of contents

1. Introductory note
   1.1 Context
   1.2 Purpose and scope of the consultation

2. Main scientific and technological challenges for frontier research in robotics and embodied intelligence that need to be tackled in the next 10-20 years, bottlenecks that need to be addressed in the medium term and nature of the challenges (vision-driven and high-risk, embryonic or foundational)
   2.1 Preliminary comment: open issues from past research agendas
   2.2 Embodied Intelligence
   2.3 Modularity
   2.4 Self*
   2.5 Service robotics
   2.6 Human-robot interaction
   2.7 Enabling technologies
   2.8 Computational architectures and neuromorphic control
   2.9 Rapid (real-time) acquisition, maintenance, and exploitation of useful models of self and world in robots and embodied systems
   2.10 Artificial metabolism
   2.11 Artificial consciousness
   2.12 Nano-robotics and molecular robotics
   2.13 Design methods
   2.14 Biology-robotics synergy
   2.15 Psychological, ethical, and societal issues

3. Research topics to include in the FET 2011–12 Work programme to foster research addressing the challenges identified
   3.1 Paul Levi
   3.2 Frederic Boyer
   3.3 Luc Berthouze
   3.4 Yasuo Kuniyoshi
   3.5 Owen Holland
   3.6 Alin Albu Schaeffer
   3.6 Eugenio Guglielmelli

4. Funding 'instruments' that FET should employ in order to support the research (small projects < 3M€ - 3yrs or large projects ~4-6 M€ - 4-5 yrs)

5. International collaboration outside the EU important for this research and organisations with whom the EU should collaborate as a priority

6. High-tech companies participation in frontier research and what makes this suitable for ICT and FET

7. Existence of a body of European researchers able to carry out research in this area and interested in submitting proposals

Annex I: Contributors (in alphabetical order)
1. Introductory note

1.1 Context

The Future and Emerging Technologies (FET) scheme fosters frontier research that opens up new avenues across the full breadth of future information technologies. FET acts as a pathfinder promoting the exploration of radically new ideas and trends for future research and innovation and provides sustained support to emerging areas that require fundamental research to be carried out over a long period. It aims to go beyond the conventional boundaries of ICT and ventures into uncharted areas, often inspired by and in close collaboration with other scientific disciplines. Radical breakthroughs in ICT increasingly rely on fresh synergies, cross-pollination and convergence between different scientific disciplines as well as collaboration with the arts and humanities over issues such as ethics and moral questions. In particular, frontier research in robotics and embodied intelligence calls for such interdisciplinary collaborations and combination of knowledge from a wide range of sciences.

Fundamental research in the area of autonomous artefacts has been pursued in FET under two earlier proactive initiatives: Beyond Robotics (2004 – 2008) and Embodied Intelligence (2009 – ca. 2012).

The **Beyond Robotics initiative** called for interdisciplinary work along three objectives:

- The development of cognitive robots whose “purpose in life” would be to serve humans as assistants or “companions”
- Hybrid bionic systems that would augment human capabilities such as perception of the environment, motion, interaction with other humans etc.
- The development of autonomous microrobot groups ('robot ecologies'), consisting of many heterogeneous members exhibiting collective behaviour and intelligence.

Proposals were to have ambitious objectives at the level of a complete system and aim at breakthroughs that go well beyond the state of the art. They were expected to seek new approaches and address and integrate topics such as multisensory perception, learning, scalability, integration, task and environment adaptation, interaction with humans, and rigorous evaluation.

Three integrated projects (COGNIRON, NEUROBOTICS, I-SWARM) and a network of excellence (EURON) were funded from this initiative. Further information of the projects is available at [http://cordis.europa.eu/ist/fet/ro.htm](http://cordis.europa.eu/ist/fet/ro.htm).

The **Embodied Intelligence initiative** called for new technologies and design approaches for building physically embodied intelligent agents and artefacts, with emphasis on the relationship between shape, function and the physical and social environment, along three objectives:

- Mind-body co-development and co-evolution through permanent and extended multimodal interaction of agents with the physical and social environment.
- Morphology and behaviour: new design principles for sensing, actuation and locomotion components and for robot architectures that are based on a deeper understanding of the role of form and material properties in shaping behaviour, and of the ways in which these afford relationships and interactions with the environment and with other agents.
- Design for emergence: design paradigms and techniques for purposive agents where behaviour is not strictly programmed but robustly emerges from the interaction of the various components (each with local intelligence), the environment and its ubiquitous information resources.

One integrated project (OCTOPUS) and five small-scale targeted research projects (LOCOMORPH, VIACTORS, EMORPH, EVRYON, ANGELS) were funded from this initiative.

In addition to the two FET initiatives, industrially oriented robotics research has been funded via Challenge 2 of the ICT Theme. For more information, see http://cordis.europa.eu/fp7/ict/programme/challenge2_en.html.

1.2 Purpose and scope of the consultation

FET aims at bringing different disciplines to work together in order to tackle grand scientific challenges and to pave the way for future information and communication technologies. This consultation was targeted to the robotics, embodied intelligence and related research communities with the view of identifying new topics for FET proactive initiatives in the next 2011 – 2012 funding phase. We therefore invited experts to present an analysis of those grand challenges and what research topics should be included in the FET work programme to tackle them. We also asked for suggestions regarding the means to implement the research – whether the projects should be big or small, or whether networking or coordination between researchers should be fostered.
2. Main scientific and technological challenges for frontier research in robotics and embodied intelligence that need to be tackled in the next 10-20 years, bottlenecks that need to be addressed in the medium term and nature of the challenges (vision-driven and high-risk, embryonic or foundational.

2.1 Preliminary comment: open issues from past research agendas

A preliminary comment, raised by Luc Berthouze and Rolf Pfeifer, is that some of the challenges identified in the past for frontier research in robotics and embodied intelligence are still open, i.e. they have not been addressed in ways such that one could confidently say that these are no longer challenges for the community. Some of the topics for investigation should remain in the current agenda. Significant progress has been achieved already in the initiatives "Beyond robotics" and "Embodied intelligence". However, many of the big challenges remain and will require extensive cutting-edge interdisciplinary research efforts at the highest international standards.

For example, one would think that 3D sensing for everyday objects and environments would no longer be an important goal (this was the focus of heavy research 20 years ago after all). Unfortunately, today’s robots are still unable to deal with apparently simple tasks such as grasping a glass (any glass), or replying to a simple query such as “pick up the banana on the table” as soon as the environment is open-ended. These are “easily” solved in lab environments, of course, and lead to believe the problem has been solved. In general, open-ended robustness is an issue that is not understood, neither conceptually, nor practically.

The main challenges identified, for example, in the "Beyond the Horizon" initiative, still represent unresolved challenges and should remain on the list of challenges and research topics for future calls. Experience with the ongoing projects has shown that the goals are more valid now than ever. What has changed, though, is that we now have a better understanding of them, especially in terms of the bottlenecks that need to be addressed in the intermediate term.

This pushes the focus on foundational challenges rather than vision-driven or high-risk challenges that end up being only superficially addressed. The effort is not so much on identifying new challenges, but also on elaborating some of the ones the Commission has been pursuing in its previous programmes and calls.

2.2 Embodied Intelligence

There is a shared view that the main scientific and technological challenges for future research in robotics, especially in the field of embodied intelligence, is expected to be the investigation of the relation between structure, function and behavior of artificial robotic systems. As pointed out by Paul Levi, we learned in the past that one particular shape is able to fulfill only several particular tasks and the adaptability to new situations or environmental changes is only possible in a very limited way.

According to Rolf Pfeifer, whenever understanding and designing intelligent systems, an account must be given (at least) at the three basic time scale: "here and now" (the dynamical system), ontogenetic and learning (life time of individual), and phylogenetic (evolution over many
generations). Moreover, there is the perspective of collective intelligence. These time scales and the collective intelligence perspective can also be used to structure the design principles.

The theoretical/conceptual challenge includes the issues described in the following.

Task distribution between control (brain), morphology and materials, and environment (as described in the concept of "Morphological computation" (Norman Packard, Rolf Pfeifer), implicit control (Koichi Osuka), intelligent mechanics (Martin Fischer)): While in traditional control theory there is a clear separation between the control and the controlled, this separation can no longer be maintained when trying to understand biological forms of intelligence. While intuitively, these concepts are plausible, a rigorous scientific treatment and understanding is still lacking. How can morphological properties (shape, distribution of sensors and actuators in and on the organism, weight distribution) and material characteristics (elasticity, stiffness, symmetries, deformability) be exploited to carry out processes required for coherent stable behavior? Understanding this issue, quantifying morphological computation, and applying the insights to design will most likely require mathematical formalisms inspired by non-linear dynamics and geometric group theory. A particularly challenging issue will be to understand the implications for learning because the biomechanical constraints deliver "preferred joint trajectories" that -- in biological systems -- turn out to be good exploration strategies (high energy efficiency, little control required, high probability of interesting event happening).

More generally, the big theoretical question is at what level to apply the control: by changing the global dynamics (e.g. by performing a morphological change, e.g. the mechanical configuration of the shoulder joint), the local dynamics can be – indirectly – influenced to perform the desired movement (i.e. the joint passively self-organizes into the desired trajectory). Another example would be controlling the stiffness of the actuator which yields a global change in dynamics.

The control of fully compliant, highly redundant systems with many degrees of freedom still represents one of the major challenges (see also "Bernstein's problem" at the kinematics level). Although it seems clear that a developmental approach will be the way to go, we don't have a sufficient understanding of the processes involved and the underlying mechanisms. Here, the cooperation with developmental neuroscience, biomechanics, and motor control, will be essential. In order to be truly adaptive, we must consider the co-development of body and neural system (and understand their cooperation).

Moreover, the cooperation of mechanisms of sensory-motor development in the individual with social interaction processes during ontogenetic development should constitute an essential research topic that hasn't been studied in any detail – mostly, sensory-motor and social interaction processes are treated separately. This point was also on the "Beyond the Horizon" research agenda but not much work has been performed on it in the meantime. This touches upon the general point of the relation of collective and individual intelligence. Recent empirical research in the social sciences seems to suggest that much of individual behavior is not so much under conscious (individual) control, but rather the result of reflex-like mechanisms and local rules of interaction.

Another issue which needs theoretical (but also practical) investigation is the one of "scaffolding". When designing intelligent systems, we should not only focus on the agent itself, but on its interactions with the environment. By off-loading tasks in the environment, the design of the agent itself can often be simplified by orders of magnitude. A systematic understanding of "scaffolding" is still lacking. This also relates to the issue of the relation between processes operating at the level of the individual and social interaction.
Yasuo Kuniyoshi envisages well-defined challenges for embodied intelligence, of foundational nature:

- Embodied Meaning: understanding the “meaning” of novel experiences consisting of multi-modal perception and motor behaviour. Capability of improvisational task accomplishments.
- Emergent Autonomy: self-organized top-down control on/from emergent behavior, autonomous active learning.

Eugenio Guglielmelli, while suggesting the concept of *Bionic Society*, where (wearable) robots share places inhabited by humans, as a reality in the next 20 years, describes the following challenge:

**From Embodied Intelligence to Structural and Evolving Intelligence.** The pervasive concept of Embodied Intelligence could be a key foundational element of 21st Century robotics. So far this concept has been typically considered as a basic “source of inspiration” for guiding the robot design process, mainly for the selection of proper morphological solutions for the robotic artefacts. To better serve the needs of 21st Century robotics, the embodied intelligence concept is being overcome and generalised towards two main novel research avenues, still in an embryonic stage:

a. **Structural Intelligence.** This line of research aims at implementing the lowest functional level of intelligence that could be embedded in a robotic artefact by tightly merging the concepts of morphological computation and emerging behaviours. When robots feature both the capability to exploit their morphology to mechanically process motor-related computations and to produce behaviours that naturally emerge from their mechanical properties, they will be considered as realising some level of ‘Structural Intelligence’. Designing for Structural Intelligence will require new approaches and tools to which a new generation of robot designers shall be trained;

b. **Evolving Intelligence (from Initial Conditions).** From the general perspective of the evolution of intelligence in robots, embodiment can be considered as an important, but limited subset of a much richer set of Initial Conditions. Like in any complex system subject to environmental influence, such Initial Conditions are expected to have a direct impact on the type of evolving intelligence that the system will develop. Topology, morphology, sensorization, spatial distribution of sensors embedded in the robot body and other features typically associated to the concept of embodiment are only part of the possible Initial Conditions of an evolving robotic system that need to be instantiated by the robot designer: basic a priori knowledge of the environment, an initial set of basic skills, starting dimensions of components that are supposed to physically grow along time, are just a few examples of the several additional typologies of Initial Conditions that need to be identified. Evolution of intelligent behaviour will also require a careful design of the environmental setup and dynamics, especially in terms of types and sequences of stimuli to be generated for eliciting and favouring the learning of specific skills. 21st century robots will probably require the implementation of dedicated INTERACTIVE BIO-REACTORS, i.e. controlled environments where the robots will evolve from Initial Conditions to the desired degree of intelligence, as required for the target application domain. Robot learning processes shall be highly cumulative, with minimal interference during subsequent learning of different skills and tasks.

### 2.3 Modularity

Still Rolf Pfeifer points out that one of the issues that has repeatedly emerged is the one of modularity. Historically, there has been an enormous amount of research on modularity in biological and cognitive systems. Because modularity not only plays an essential role in
understanding, but especially in design, modularity should be explored at all levels. Here, evolutionary and developmental approaches will be required to provide, ultimately, the desired insights (see also the research on models of genetic regulatory networks). When discussing modularity, it is essential to keep morphological and material properties in mind. For example, the notion of movement primitives, which is, in essence, based on neural circuits for particular elementary movements, should be extended to incorporate morphological and material characteristics, i.e. the relevant "modules" should not exclusively be viewed as "neural".

Paul Levi outlines that modular robotics waked up new ideas to cover the problems of adaptability, not only in the field of research but also in many industrial applications. Such systems required new ideas on how, on one hand, to allow similar capabilities typical of a complex robot and, on the other hand, to reduce the complexity that arises through modularity. Classical control mechanisms seems to be useless and therefore cannot be applied. It seems that we are now at the starting phase and we have first to learn how to control such systems.

2.4 Self*

According to Paul Levi, to apply all self* characteristics to modular systems is one of the major challenges. Yasuo Kuniyoshi also identifies self-repairing and self-configuration with integrity as one of the embryonic challenges to be faced. More specifically, he refers to self repairing with respect to arbitrary or unexpected damages/failures and to self reconfiguration in response to novel situations/tasks. In any case, self integrity must be maintained, including maintaining the mission, experience, knowledge. A very interesting concept is proposed by Frederic Boyer, as new robots capable of self-displacing in very unusual environments as granular media (which are neither fluids nor solids).

2.5 Service robotics

The field of service robotics is getting ever broader and more varied, less clearly defined, and it starts blending with many other disciplines: computer science, engineering (electronic, mechanical), artificial intelligence, cognitive science, biomechanics (sports science), developmental robotics, evolutionary robotics (including morphogenesis), ubiquitous computing (ambient intelligence), man-machine interface technology, cyborg technology (non-invasive, invasive), assistive and rehabilitation robotics, prosthetics, network robotics/swarm robotics, nano-robotics, self-assembly/self-repair/self-reproduction, material science, bio-materials (sensors and actuators, including energy management [storage and deployment]), etc. All of these areas bear the potential for innovation and breakthroughs.

However, Rolf Pfeifer underlines that we have to be clear what goals we are pursuing with our research: is it foundational, irrespective of potential applications? Is it "oriented research", specifically focusing on particular domains such as home robotics (also called "domotics"), minimally invasive surgery, prosthetics, factory automation, etc.?

One of the uncertainties in these potential application areas is whether the people will actually want these products – it’s ultimately a question of economics, of what survives in the global competitive markets. Making such predictions has, in the past, proven to be difficult if not impossible, there have been tons of wrong predictions (telephone, flight, etc.), where people could not imagine any kind of useful application (e.g. business applications of the telephone).

We see many scenarios where humanoid-like robots perform domestic tasks, helping in particular the elderly maintain a maximum level of autonomy. Will these robots be mobile, i.e. do they have to move around? In many cases, a much simpler solution might do the job, e.g. a conveyer belt (as in the kaiten sushi bars) (see also "scaffolding").
In standard one-level apartments, wheeled robots seem sufficient: although they do have some obvious limitations (not being able to move over rough terrain and stairs), they are orders of magnitude cheaper and more robust than legged ones. In this case, there is no need for walking. Irrespective of the amount of progress, walking systems will definitely be more fragile and expensive and less energy-efficient than wheeled solutions. So should walking (or locomotion over rough terrain) be a research topic? Then there is the notorious energy supply problem for autonomous systems, which is far from a solution. Should this be a research topic? Only if mobility and autonomy are desired features.

One central characteristic of biological humans is that they can do a host of tasks, but hardly any of them really well: for most of them there is a specialized machine that can do it faster, more precisely, more efficiently, and more cheaply. Will, therefore, a human-like robot be economically viable or will our environment of the future be populated more by many specialized machines? We don't know at this point in time.

According to Rolf Pfeifer, the grand goal of creating intelligent systems for the real world remains to be a highly productive one, offering huge challenges that will all constitute breakthroughs in our quest for intelligent machines. The insights achieved will benefit all the other areas involved in the development of such intelligent robots. Each of the areas, biomechanics, materials, prosthetics, nano-robotics, provide, of course, their own huge challenges.

For Daniela Rus, the main challenge to be tackled in robotics is to build more agile machines that can be better maneuvered than current robots (on the ground, in the air, and in water).

Frederic Boyer envisages the design of very small and simple swimming robots whose simple interactions can create a collective behaviour suited to the realisation of a given task.

### 2.6 Human-robot interaction

As pointed out by Eugenio Guglielmelli, one of the well acknowledged great challenges in robotics is the development of intelligent artefacts really able to cooperate with humans in order to improve the quality of life of a large sector of society, with special emphasis towards elderly and disabled people. He suggests that the spreading of robots sharing places inhabited by humans, wearable robots, and civil automation (including domotics but also urban planning) will shape the future “bionic society”, which will become a reality in the next 20 years.

Daniela Rus indicates the challenge to build more intelligent machines that are more capable and integrate perception, action, and communication into a system capable of interacting with humans and with other machines at higher levels than is currently possible.

Yasuo Kuniyoshi also poses a vision-driven, high-risk challenge concerning human assistance: providing cognitive/physical assistance in such ways that the user’s motivation towards the target activity is raised, rather than passively relying on the assistance. In this vision, the system should monitor the mental/physical state of the user and dynamically change or adapt its assistance.

Alin Albu-Schaeffer indicates the design of algorithms for robot assistants and companions as a main challenge, too. The lack of such robotic systems today is mainly due to the fact that today’s perception (recognition of objects, situations, and relations) and action (decision, planning) algorithms are not able to deal with the complexity of human environments and human actions.

One of the fundamental questions for Rolf Pfeifer will be “intention detection”: how does the system – however autonomous – know what the human wants. Intention detection has to function at
many levels. We can type commands – if there is a limited number, this will be straightforward. Natural language communication will be ambiguous, gestures and non-verbal communication as well. In prosthetics, this is the essential question: what should the prosthetic device do? In neuro-prosthetics, the idea is to get the intention from the neural signals and possibly other physiological signals. In a wheelchair, these signals could come perhaps from a joystick, but also from physiological variables, brain signals, and external sensory information, etc. Here, the level of autonomy of the device has to be clearly identified.

2.7 Enabling technologies

Rolf Pfeifer outlines how the performance of biological sensing systems, e.g. vision (event-based retinas), skin sensors (touch, temperature, change), and sensors integrated into the materials and actuators, is still far superior to the ones of artificial systems. Compliant materials (for sensors/actuators, body structure), deformable tissue, with dynamically changing characteristics, are still not available off the shelf – only rudimentary laboratory prototype exist. The availability of such materials would most certainly entail an almost instantaneous breakthrough in intelligent robotics.

2.7.1 Actuators

Most contributors agree on the need for tackling the challenge of more intelligent, compliant, adaptable, and efficient actuators, which still represent a bottleneck for the development of robotics and embodied intelligence.

Paul Levi thinks that embodied intelligent systems have to go beyond the classical approaches and have to be able to combine new materials like for example the Shape Memory Alloy with new design approaches and create new generations of intelligent actuators. Adaptive structures allow to create adaptive behaviors. The research in this field is in a huge progress however is still a bottleneck for modular robotics.

Rolf Pfeifer targets energy-efficient, compliant, robust actuators, as we know them from biological systems. These developments will require, of course, a close collaboration between engineering and the material sciences. The ability for dynamically changing the actuator characteristics should be on the top of the research agenda. Because actuators in themselves have "control properties" (because they are themselves physical dynamical systems; e.g. turning back into a natural position after performing a task), these developments have to closely interact with the theoretical ones on morphology and control. Also, the concept of an "actuator" might have to be theoretically clarified, given the new perspective of embodiment.

According to Owen Holland, a foundational challenge is the design and control of multi-d.o.f. articulated robots with variable compliance actuators. The human body is a multi-d.o.f. robot chassis with variable compliance actuators. It is also the best available robot chassis, and therefore may be worth copying. Although there are several FET projects looking at variable compliance actuators and individual articulated ‘limbs’, plus one looking at a compliantly-actuated multi-d.o.f soft-bodied robot, plus one CogSys project looking at a complex articulated humanoid with fixed-compliance actuators (ECCEROBOT), there is an unfilled gap. We need to know what advantages variable compliance offers over fixed (but non-linear) compliance in the context of a useful multi-d.o.f. articulated robot. There do not appear to be any conceptual barriers. However, the development of a variable-compliance actuator suitable for deployment on a mobile humanoid is a significant unsolved problem which may amount to a bottleneck – but there is much work to be done on control systems before we reach that point.
In Tamar Flash’s vision, a great challenge that has been discussed for years and has not been met so far or has not led yet to sufficiently satisfactory solutions is the ability to develop biological muscle-like actuators – this is a real challenge which is apparently technologically very difficult to solve or has not been addressed with enough human/technical resources until now. Major efforts should be directed towards meeting this challenge. This research direction requires efforts in developing:

- appropriate materials
- mechanical architectures of muscles with modifiable stiffness/impedance
- muscle-like synergies composed of many muscles that can operate in a biological manner with the ability to recruit a changing number of muscles according to task demands.

2.7.2 Sensing
Frederic Boyer indicates as a main challenge to design sensors and algorithms bio-inspired from active sensing.

2.7.3 Control
Alin Albu-Schaeffer supports the challenge of designing robots to be as fast, powerful and efficient as humans. Embodying intelligence into new actuator and sensing systems will go along with the design of new planning and control algorithms for using the new technologies.

2.7.4 Learning
According to Tamar Flash, more efforts should be paid to develop truly adaptive autonomous systems capable of learning from experience which is one of the current bottlenecks.

2.7.5 Energy
For Rolf Pfeifer, a huge technological challenge related to actuators remains to be "energy". Biological systems have entirely different solutions to this problems from current technological ones. Depending on the application area, e.g. for many applications in service robotics, having energy-efficient actuation, sensing, and processing systems (e.g. neuromorphic computing) will be crucial to the success. This is obvious for actuators, but it is also essential for sensing and processing because even though today's digital systems are, in some sense, energy-efficient, they do not compare with the efficiency of biological neural systems (which are analog and use only a fraction of the energy of digital chips for comparable "computations").

2.7.6 Materials
According to Rolf Pfeifer, growing materials is an issue that should remain on the research agenda, especially because the interaction of morphological, material, and neural systems are still insufficiently understood. Part of the problem might be precisely that such materials are still not available and therefore, systematic experimentation is difficult. Good starts have been made in "mimicking" morphological changes during development by freezing DOFs and freeing them if the basic sensory-motor skills have been acquired.

Daniela Rus also feels the need for fusing the progress in machines and materials in order to build machines that are softer and more flexible like materials.

Frederic Boyer also points out that the challenge of designing very redundant actuators and sensors with many functions should focus on their integration into new materials.

2.7.7 Electronics
Paul Levi states that, in addition to mechanical design, electronics play a major role and should not be neglected. Adaptive mechanical structures require adaptive electronics which is not self-evident and is at the moment also a bottleneck.
2.8 Computational architectures and neuromorphic control

The development of new imaging techniques suggested by Tamar flash (see below) should be augmented also with strong emphasis on research and developing new ideas about computational architecture and theoretical and computational neuroscience research focusing on the topics of:

- distributed processing by means of multi-modality sensory and motor networks combined of many -smaller networks or of modules like those which current imaging (MEG and fMRI studies) have enables to identify;
- developing new information processing technologies appropriate for "multi-modal" short range and long range information processing networks" Inspiration can be taken from current and future knowledge on cortical organization and problems solved in such networks (recurrent-connections, lateral connections, binding);
- emphasis on new ideas and focus on the issue of neural representations from mathematical perspectives trying to better understand and identify the computational mechanisms underlying the biological solutions for classical problems such as inverse kinematics/dynamics which remain open problems.

But supporting research which allows us to get closer to deciphering the neural mechanisms subserving important aspects such as binding, compositionality etc.

Neuromorphic computing should definitely remain on the research agenda, in Rolf Pfeifer’s opinion. This will require technological breakthroughs in neuromorphic engineering.

2.9 Rapid (real-time) acquisition, maintenance, and exploitation of useful models of self and world in robots and embodied systems

This challenge is proposed by Owen Holland, as a foundational one.

Rapid acquisition of a world model requires the use of distal sensing (e.g. active or passive vision) and the use of previous learning, especially from proximal sensing, to resolve ambiguities. Maintenance involves the use of fresh information to modify and augment the existing models rather than continually re-acquiring them from scratch. Exploitation involves using them for planning (from strategic to motor control levels), imagination, episodic memory, perspective taking etc. The development of these technologies will be critical for progress in both articulated robots and soft-bodied robots.

There are no conceptual bottlenecks as regards the architectural components of this requirement. However, the exploitation aspect is subject to a bottleneck. For example, the maths and physics behind the acquisition of geometrical world models using vision is essentially a solved problem (see e.g. the work at ICG Graz http://www.icg.tu-graz.ac.at/) but the availability and methods of exploitation of sufficient computer power to deliver results in real-time (say with a delay of the order of 100ms) in a package suitable for a robot is a show-stopper at the moment. GPUs (Graphics Processing Units) are certainly the way forward, but the power and space requirements for suitable multiple GPU systems (of the order of 6kW and 60 litres for a system with 7,680 cores) must be brought down by a factor of ten or more before onboard deployment is feasible. GPU technologies are dominated by the US. The problem of programming GPUs is essentially the problem of parallel computing, which is still essentially unsolved; again, US initiatives are in the lead, mainly due to the support of hardware manufacturers (e.g.http://www.nvidia.com/object/io_1209593316409.html).
2.10 Artificial metabolism

The pioneering work into energy autonomy in robots at the University of the West of England (http://www.ias.uwe.ac.uk/Energy-Autonomy-New/New%20Scientist%20-%20EcoBot%20II.htm) and its development within the EU ICEA project has shown the possibility of exploring what is one possible solution to the perennial problem of powering robots, that of developing an artificial metabolism. However, the obvious difficulty of the work means that a great deal of wider-ranging investigation will be required before the general concept is translated into true feasibility. The microbial fuel cells used by UWE are just one approach, and the solution may lie elsewhere. What is needed, in Owen Holland’s opinion, is a fundamental analysis of the problem, and a systematic investigation of all the various possibilities.

There are no obvious current bottlenecks for this embryonic/foundational challenge, other than the huge gap between the generation of power, and the generation of useful amounts of power. It is not known whether this problem could be solved by incremental development e.g. of microbial fuel cells, or if some other technology may be able to deliver useful power from the start.

2.11 Artificial consciousness

Artificial consciousness, or machine consciousness, proposed by Owen Holland as a visionary/embryonic challenge, is a subject that has developed over the last decade or so in the context of interested but fairly isolated individuals, and a lack of funding (to date there has only been one major funded project anywhere on the planet, in the UK). The development has been held back by the dominance of outdated philosophical beliefs, religious prejudice, and a concern among academics that it is a route to career suicide. Europe is the leader in the level of activity (perhaps because the prejudices and career risks are less than in the US) but this activity has not yet been translated into concrete achievement, or even an agreed programme of work. The single journal in the field was founded this year, mainly through European efforts. What is needed right now is a coherent and well defined programme of research into the engineering aspects of consciousness, and into the cognitive aspects of consciousness-related phenomena, in order to explore experimentally the possibility of constructing a conscious artefact.

There are many apparent conceptual bottlenecks, at least some of which are illusory. A key problem is that many who feel entitled to offer an opinion and a judgment of the possibility of the enterprise are unfitted to do so by their ignorance of recent research in consciousness science, particularly the relevant parts of neuroscience. On a functional level, there are several more or less settled models of consciousness (for example Global Workspace Theory) that have never been implemented on a real robot to allow comparisons with human conscious functioning; much of this work could be undertaken more or less immediately because the necessary computational and robotic substrates already exist. The major bottleneck identified by critics is that it would be impossible to determine whether an artefact was conscious or not; these critics are almost always ignorant of the progress already made in the field of machine consciousness and neuroscience in dealing with this.

2.12 Nano-robotics and molecular robotics

According to Paul Levi, another grand challenge seems to be in the field of nano-robotics and molecular robotics which has to be pushed forward to allow advanced use in health care and environment protection.

2.13 Design methods

In Eugenio Guglielmelli’s vision, the robots of the future will be designed by multidisciplinary teams mastering diverse expertise in mechatronics, (synthetic) psychology, bioengineering, industrial design, human factors, automation and domotics. Robotics technology itself has to evolve
from the current design paradigms, deeply rooted in its industrial past, towards more specific rules and *modi operandi*. 20th Century Robotics has incrementally evolved from industrial to service and advanced robotics by using the same enabling technologies. 21st Century robotics is expected to evolve on a largely independent path by making use of disruptive innovation in components, materials and system design so to properly address a large novel variety of human-centred application domains.

A main challenge are the design methodologies for 21st Century robotics. The lack of basic reliable well-performing engineering tools for mastering complexity is slowing down the development of robotics, which proceeds with a pace that is, by far, slower than expected over the past twenty years. In a sense, it appears as necessary to focus on the factors enabling the speeding up of the development processes (as it happened in the computers industry with VLSI technologies). A real impact in the future of robotics can be achieved in the medium term if an important, coordinated research effort is made in terms of basic technologies and design methodologies.

### 2.14 Biology–robotics synergy

Alin albu-Schaeffer states that narrowing the gap between robotics and biology should be one of the main challenges. In a scientific sense, robotics is trying to understand human and animal behaviour by constructively reproducing their high level functionalities. This is a fundamentally different approach than the one taken by biology. Already today, a strong cross-fertilisation between robotics and biological sciences (e.g. biomechanics, psychology) can be observed. One would expect that the two areas will continually approach each other within the next decades.

Tamar Flash more specifically outlines a need for closer synergism between basic research in neuroscience and robotics building upon new innovative techniques and findings in neuroscience from which future research in robotics and especially embodied intelligence can benefit. For example, the need for developing new innovative imaging techniques of neural cell assemblies and getting further understanding into their modes of activation in vivo can highly benefit the ability to gain better understanding of brain activations in moving animals which can allow to gather more information about sensory information processing and motor control mechanisms in behaving animals. Such new imaging techniques should be developed for both brain and spinal cord systems.

### 2.15 Psychological, ethical, and societal issues

Rolf Pfeifer states that there are some fundamental psychological, ethical, and societal issues involved. Do we really want autonomous systems, i.e. systems that can take decisions on their own (whatever that exactly would mean)? Those systems that we have at the moment and that work autonomously around the clock have extremely narrow "ecological niches". Good examples are air-conditioning systems, refrigerators, elevators, autopilots, and trains (subway, e.g. line 14 in Paris Metro, the Dockland Light Railways near London). What else can a train do but accelerate, slow down and stop? Still, it took many years for these systems to reach the real world.

In most economically developed Western societies, there is a high level of technology skepticism around, in particular where intelligent systems are concerned. It would be important to put "social studies" on the research agenda, that investigate how people perceive technology, their fears, and what might be done about it. Often, communication is insufficient, with researchers overestimating the implications of their own achievements.

Promoting educational applications, which are already part of a number of projects in the 7th Framework Programme, will be extremely important for a number of reasons: First, robotics turns out to be an extremely efficient educational facilitator for teaching powerful ideas. Second, employing robots for education at a very broad scale will prepare the future generation for advanced
technologies. And third, an educational perspective, implies the need to communicate the very essence of scientific insights, it forces the researchers to make – appropriate – abstractions from the technical details required for complex systems. In this sense, an educational perspective goes to the heart of the research insights and is not purely a "development of educational toolkits".
3. Research topics to include in the FET 2011–12 Workprogramme to foster research addressing the challenges identified.

3.1 Paul Levi

The upcoming research topics should be motivated by real world applications (surface, water and air applications) and should address common problems in the fields of modular-, nano-, and bio-inspired robotics. Materials research should not be neglected, too.

3.2 Frederic Boyer

Some topics should be included which promote and develop new (bio-inspired) technologies and devices exploiting the physical properties of contact (mechanics, electric…) at small scales (materials, microstructures, surfaces…) whose effects are exploited at large scales for improving robots performances. In particular, this should be considered for what regards locomotion and perception for autonomy.

3.3 Luc Berthouze

The one particular research topic that I believe would contribute to foundational progress is the notion of on-going emergence of complex behaviours. I do realise it is partially included in the previous call but to date there isn’t any framework that is developed/operationalised enough that it could be transferred in a robust manner to any platform. Most of today’s systems are capable of learning one skill. There is very little work demonstrating an adaptive form of hierarchical acquisition of skills whereby the agent acquires a new skill, combine it with another, and increases the complexity of its behavioural repertoire. My personal take on these issues is that the focus of the call should be on development because in such a context, these concepts become a lot more tractable (albeit still extremely difficult).

One particular research topic that would contribute to foundational progress is the notion of on-going emergence of complex behaviours. Whilst it is partially included in the previous call, to date there isn’t any framework that is developed/operationalised enough that it could be transferred in a robust manner to any platform. Most of today’s systems are capable of learning one skill. There is very little work demonstrating an adaptive form of hierarchical acquisition of skills whereby the agent acquires a new skill, combine it with another, and increases the complexity of its behavioural repertoire. My personal take on these issues is that the focus of the call should be on development because in such a context, these concepts become a lot more tractable (albeit still extremely difficult).

Remaining in the domain of development, an important vision-driven challenge is that of actual morphological development. Most work in that area is at the level of simulation or very simple system. The iCub was a good first step toward understanding the relationship between growth and development, but the absence of actual physical growth makes it impossible to really study the co-development between brain and body. We need to see systems that physically grow, that are compliant (not just in terms of how the system is controlled but also in terms of the hardware), and that change their physical characteristics. The best way to do this is likely to strengthen collaborations with the physical and biological sciences and aim for new hybrid materials.
3.4 Yasuo Kuniyoshi

Two years is too short a period for solving any of the above problems. However, deeper analysis of the problems and identification of some common foundational problems and concrete example scenarios can be done. Probably, some pilot study projects plus a series of workshops are suitable.

3.5 Owen Holland

- Methods and architectures for the rapid (real-time) acquisition, maintenance, and exploitation of useful models of self and world in robots and embodied systems.
- The development of an artificial robot metabolism capable of delivering useful amounts of power (order of tens or hundreds of watts) in a range of unprepared terrestrial or marine environments.
- Methods for the design and control of multi-d.o.f. articulated robots with variable compliance actuators.
- The development of machine consciousness in the form of a successful control system for a complex robot that uses critical functional components related to those thought or known to be involved in consciousness.

3.6 Alin Albu Schaeffer

- Design of novel actuation and sensing capabilities, very much on the line of the current “Embodied Intelligence” project. One can observe that most of the currently funded projects within this FET Call focus on the development of such interfaces. One has to sustain these efforts for longer research time than only a three year project. The inspiration from biology and the interplay with biological sciences is equally important as encouraging of new engineering design principles for sensors and actuators. “Soft Robotics” refers in this context not only to novel, more efficient, compliant actuators, inspired by biological tissue and contrasting to today’s rigid and inefficient robots, but also to planning and control algorithms for using this new technology.
- “Human-Robot Interaction”. This interaction is understood both in a cognitive sense (designing new software and hardware interfaces to humans, methods for interpreting and understanding human behaviour) as well in a physical sense. Physical interaction is what distinguishes robots from computers and poses many open questions to robotics.
- “Scalable Algorithms” One typical nasty questions on a robotics conference is “How does it scale?” – related to perception and action algorithms. (The second nasty question is “When will it become commercially available?”). The first question reflects the fact that most solutions and algorithms apply to toy or small, limited scope problems, but mostly fail in a typical human every-day environment. Is it just a problem of computing power? Probably we have to deal here with more fundamental questions about the architecture of our robotic software for being able to recall and combine a large set of methods and apply them to new problems which are similar to tasks previously solved by the same or other robots.

3.7 Eugenio Guglielmelli

Research topics should address the basic technologies and design methodologies capable of speeding-up the development cycle of robots interacting with the humans or operating in human environments. In particular, the following research topics deserve a coordinated research effort:

3.1.1 Novel actuation paradigms

Actuators are key components for motion generation and control and, as such, their properties greatly impact on the overall performance of actuated systems. There are several applications where the unavailability of suitable actuators hinders the development of well-performing machines. If we
take into account, just to mention an example, the field of wearable robotics, which include limbs prostheses, active orthoses and assistive exoskeletons, we can see that the development of dexterous, lightweight and cosmetically pleasant systems is largely hindered by issues related to currently used actuators, such as electric motors or fluidic systems, which are often too bulky, require batteries or pumps/compressors. On the other hand, the so-called smart materials do not provide the necessary energy/power densities, or are not robustly controllable.

If we look at the metabolic processes taking place in muscles, we see that biochemical reactions are the only actuation strategy used by Nature. The performance of biological muscles is indeed very far from being equaled by any artificial actuation systems developed so far in terms of low weight, energy/power density and controllability.

Evidently, we have to be aware that reproducing such natural processes is not a feasible task due to enormous technological limitations compared to Nature. Anyhow, we believe that novel actuation technologies should take inspiration from nature at a higher level of abstraction. In particular, it is useful to systematically investigate how chemistry can be fruitfully exploited for direct mechanical energy production.

Besides investigating novel chemical processes suitable to be exploited for direct chemo-mechanical energy transduction, it also important to develop adequate kinetic models in non-equilibrium conditions for an accurate and energy efficient control of the actuation unit, as well as efficient, bioinspired control techniques for a robust and safe performance.

3.1.2 Intelligence embodied in the human-robot symbiotic system

The interaction between a robotic artefact and the human body can benefit from the intelligence embodied in the robot itself. But the exploration of the intelligence embodied in the human body is still an almost virgin field, promising new research avenues. Indeed, researches in bipedal walking has demonstrated that complex tasks can be obtained as dynamically emerging behaviours. Investigating how artificial and biological embodied intelligences may interact and may lead to symbiotic dynamic behaviours offers a novel approach for achieving seamless interaction between the human body and the robot. This research topic is across robotics, biomechanics and neurosciences. In particular, the investigation of neural processes shaping human actions is considered as the preliminary input to the design of novel robots better interacting with humans.

3.1.3 Simulating robots with humans-in-the-loop

While the simulations of robots, including mechanics, control and interaction with an environment, can be performed with an acceptable confidence in-silico, using a number of tools available, the reality gap becomes evident when the interaction with a human must be taken into account, because the human offers both unconscious and volitional reactions to external inputs, such as those provided by the interaction with a robot. The aim of this research topic is to pave the way towards the development of a simulation environment where the human-robot interaction can be explored in a more comprehensive way, starting from the exploration of psychological and neuroscientific aspects.

The development of tested metrics for the a-priori evaluation of the qualitative and quantitative features of the interaction (perceived affordances, ergonomics, acceptability) is considered as a strategy for dramatically shortening the development cycle of robots interacting with humans.

3.1.4 Novel approaches to motion generation & sensorimotor control

Motion planning, generation and control is mainly still based on approaches incrementally derived from industrial solutions. The investigation of motion generation mechanisms of biological systems can notably change the traditional approach to robot motion generation and control. Motion generation, typically obtained by means of trajectory planners of different complexity, and motion
control aiming at generating the control command cannot be regarded as two separate modules; they are strictly interconnected by the achievement of common objectives of motion efficiency. This implies the possibility of jointly acting on the couple planner plus control to address specific task requirements. The main idea of the novel approach to motion generation and control is to close the feedback loop on trajectory planner as well as on control in order to simplify control whenever possible with a corresponding increase of complexity of the planner. A simplification of control can entail notable benefits in terms of computational efficiency, robustness and stability of the system. Recent studies on intermittent nature of motion control and real time composition of motor units for motion generation of human and monkey upper limb are inspiring key issues for this research topic. Another important feature of novel generation of robot controllers is the capability of coping with deformable, instead of rigid, robot structures. Compliant joints, actuators, links will be typical components of the 21st century robots, and adequate sensors and control strategies should allow to compensate for the non-linear behaviour and the potential inaccuracies introduced by such components.

### 3.1.5 Distributed human-robot interfaces

To design robotic systems able to autonomously operate in unstructured environment with enhanced capabilities of decision making, learning and interaction is currently one of the main objectives of robotics. Perception plays a role of paramount importance to achieve it. However, the use of interactive distributed sensor networks embedded in the operative environment is still far to be fully exploited to enhance robot performance, especially in those applications requiring tight interaction with humans. The key issue of this research topic is to extend the perception system of robots to external environment by embedding networks of sensors not only in objects and other environmental elements but also in/on human subjects which robots are expected to interact with. The main expected result is a strengthening of robot capabilities to anticipate and understand the human behaviour and correspondingly increase its capability to reprogram, autonomously modify its behaviour, incremental learn how to address new contexts and safely interact with the environment and humans.
4. Funding 'instruments' that FET should employ in order to support the research (small projects < 3M€ - 3yrs or large projects ~4-6 M€ - 4-5 yrs).

Most contributors consider both kinds of instruments, i.e. small projects < 3M€ - 3yrs and large projects ~4-6 M€ - 4-5 yrs, suitable and needed. They are indicated for different challenges and different objectives.

As Paul Levi points out, a good mixture of both, small and large projects is necessary as they can serve different purposes. Within the large projects more advanced topics with a high critical mass of researchers can be covered. They can define the research fields and forward new technological breakthroughs. Whereas small projects can focus on specialized topics with small highly integrated teams. The ideas for new small projects can be lined out from the large projects and can provide deeper investigation on certain levels.

Similarly, for Luc Berthouze a theoretical understanding of development does not necessarily require large financial investments, whilst work in the area of morphological development could involve large costs.

Alin Albu-Schaeffer considers appropriate the mixture of small and large projects that is now within “Embodied Intelligence”. For the case of large projects, it is important to ensure that the research groups are really working on a common topic and are well networked. Often, IPs collapse in practice in several smaller groups. In such a situation, STREPs would be more appropriate, due to less managerial overhead. However, 4-5 years of research on a well focused topic and with a group of 5-6 partners (a longer STREP) would probably be an interesting alternative.

For Eugenio Guglielmelli, both instruments should be employed, but with a larger investment (60-70%) on large projects. There is a need to mobilise a critical mass of resources on a few foundational initiatives that could pave the way for 21st century robotics.

Making a specific reference to the challenges outlined, Owen Holland indicates both instruments for real-time modeling. Progress requires the development of proof of concept systems for individual components (small projects) and at least one major large project to show how all necessary technologies can be implemented and integrated to demonstrate functional advantages. For the artificial metabolism challenge, the present urgency is for small scale proofs of concept, and so small projects would be appropriate at the moment. For multi-d.o.f. compliant robots, a large project context is more appropriate, given the mix of technologies that will be necessary. Finally, either a very large project examining a number of approaches, or several self-sufficient small projects each exploring a possible route to artificial consciousness could be employed.

However, Frederic Boyer and Yasuo Kuniyoshi consider large projects more suitable for the challenges described above. This is based on previous experience mostly acquired on national projects (4-5 years) and on the consideration that coherent understanding of the issues needs to be established. Each topic requires a combined approach from multiple disciplines.
5. International collaboration outside the EU important for this research and organisations with whom the EU should collaborate as a priority.

Most contributors, both from EU and outside the EU, consider the collaboration with countries outside the EU important for frontier research. Paul Levi thinks that the international collaboration is a very powerful instrument for researchers and sees a big challenge in bringing the leading researchers together. Especially, countries like the USA, Japan, India and China should be moved into the focus. There has to be a better exchange of research results and coordination of researchers. A worldwide funded group can establish better ways of knowledge transfer and can fund the exchange of researchers.

For Frederic Boyer American labs are quite advanced on many of these topics (e.g. Northeastern University or Carnegie Mellon University).

Daniela Rus, from US, thinks it is critically important that the EU forges international collaborations and especially collaborations with the US. At the moment there are very few opportunities for EU and US to work together; on the other hand there are many more opportunities for collaborations with Asian countries.

Yasuo Kuniyoshi also thinks that the international collaboration is very important. Japan is one of the front runners in the above issues. Particularly, University of Tokyo, Osaka University, National Institute of Informatics and Tohoku University.

Alin Albu-Schaeffer thinks that the possibility to cooperate with groups from US and Japan is important. One possibility would be to define joint projects and have European partners funded by ICT and partners from overseas funded by their own governments within the same project.

For Eugenio Guglielmelli, co-operation with other major funding agencies in US, Japan and Korea could very beneficial to identify new ways of international collaboration. Synchronisation of regional funding schemes in order to enable the establishment of international research consortia carrying out joint projects would is a very desirable goal. Another important topic to be promoted at international level is the support to joint initiatives for benchmarking, such as public robot competitions. For instance, an international challenge modelled on the DARPA robotic challenges initiatives could be very nice and timely to be implemented. An initiative similar to the DARPA Challenge at EU level would be highly beneficial anyway, even if international cooperation could not be fully realised.

Making a more specific reference to the modeling challenge described above, Owen Holland thinks that progress enabling deployment is unlikely without the support of a major multicore/GPU manufacturer such as nVidia, perhaps through a link with one of their sponsored research institutes in the US (e.g. the Stanford PPL), while he does not see a need for international collaboration for the other challenges, as there are sufficient resources within the EU. More specifically, in the case of artificial consciousness, Europe is already in the lead, and we should exclude collaborations outside the EU to strengthen and capitalise on this position.
6. High-tech companies participation in frontier research and what makes this suitable for ICT and FET.

The participation of high-tech companies in frontier research is desirable with specific roles, like the development of the hardware needed for the research, system integration and field testing, and in general the exploitation process at the end of projects. Spin-off companies are preferable for this role. On the other hand, many challenges are more suitable for university research and require academic contribution.

Paul Levi thinks that industrial partners should be better integrated into the projects to support the engineering process with their knowledge in production. They can give feedback for the development of future technologies, which will be demanded by a broad market.

For Yasuo Kuniyoshi, in the self repair/reconfiguration theme, the participation can greatly reinforce the hardware development. In the encouraging human assistance theme, the participation is important for system integration and field testing.

Alin Albu-Schaeffer suggests to support the emergency of spin-off companies which to use and commercialize the outcome of the projects in addition to attracting big high-tech companies. The experience shows that small spin-off companies often have higher motivation and efficiency in promoting these new technologies.

Eugenio Guglielmelli, too, thinks that it would probably be useful if specific project resources for exploitation could be directly allocated to support the start-up of new (project) spin-off companies in the final stage of the project lifecycle. Ideally, these resources could be used not only to provide services to the new company but also as a seed-capital to be actually invested only if the project successfully achieves its objectives and if a credible business plan can be produced. Way-out strategies should be carefully defined so that this capital could later be re-invested in other EU R&D initiative after a number of years (e.g. 3 to 5).

However, Luc Berthouze believes that foundational challenges require academic contributions before industrial contributions. The constraints of developing prototype hide the fact that the concepts are not properly developed.

This is also the opinion of Owen Holland, who thinks that the challenge of artificial metabolism is certainly more suitable for university-based research, although UWE’s experience indicates that some of the manufacturing requirements may require access to commercial micro- and nano-scale technologies. Similarly, the challenge concerning multi-dof compliant robots is more suitable for university research, unless one comes up with a suitable variable compliance actuator. Artificial consciousness is definitely a programme that depends on conceptual rather than technical progress. On the contrary, the challenge of modeling would require an industrial contribution concerning GPUs. However, it seems there is not any suitable European company in the area of GPUs. It is certainly within the scope of ICT and FET; the architectural component could possibly fit within Cognitive Systems and Robotics, but the more generic GPU technology and programming requirements are more appropriate for FET.
7. Existence of a body of European researchers able to carry out research in this area and interested in submitting proposals.

There is a general agreement that there is a body of European researchers able to carry out research in this area and interested in submitting proposals.

However, Luc Berthouze raises the question that the principle of always looking ahead to the next 15-20 years’ challenges makes it less attractive to researchers to actually pose and properly assess where the state of the art actually is. There is a huge gap between what is being claimed and what is actually available. Reading the previous FET description, one would assume that we could routinely see a humanoid robot placed in a real world home go to the kitchen, pick up a glass, fill it up, and bring it to his carer without any intervention, remote control, etc. Yet, that isn’t the case.

Owen Holland thinks that there are several groups able to contribute to the individual architectural components of real-time modelling (e.g. real-time vision) but very few who appreciate the necessity of an integrated and real-time system-based approach. Any project would require a clearly articulated vision and strong leadership – difficult under the consensual model of EU multi-partner research. Concerning artificial metabolism, we know only of UWE’s work at the moment, but this will not be enough on its own to solve this problem, and the known availability of significant funding will be necessary to stimulate interest elsewhere. For the multi-dof compliant robots, instead, there are many university and research institute groups involved in the component technologies, and there surely would be strong and high-quality response. Finally, there definitely are EU groups able to carry out research on artificial consciousness and to submit proposals on this topic.

Eugenio Guglielmelli observes that since the proposed topics span outside the strict robotics field, and opens to other disciplines such as Chemistry, Biology, Materials, Ergonomics, Psychology, and Neuroscience, the targeted researchers may be more than those usually benefiting from FET initiatives. Moreover, there is a clear opportunity to bring in Robotics fresh energies and ideas from apparently far yet contiguous fields, as in the spirit of the FET programme.

EU groups explicitly mentioned are Perada’s group (mentioned by Paul Levi), which is one group of European researchers with the focus of bringing together researchers from different fields and different countries in order to investigate pervasive adaptation for multiple applications and the following ones (cited by Yasuo Kuniyoshi):

- University of Zurich, Switzerland: R. Pfeifer’s group
- EPFL, Lausanne, Switzerland: D. Floreano, A. Billard, A. Ijspeert
- IIT, Genova, Italy: G. Sandini & G. Metta
- Scuola Superiore Sant’Anna, Pisa, Italy: P. Dario & C. Laschi
- ETH, Zurich, Switzerland: R. Siegward
- TUM, Munich, Germany: M. Buss & G. Cheng
- University of Karlsruhe, Germany: R. Dillmann.
Annex I: Contributors (in alphabetical order)

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