National Research Council of Italy

# HIGH LEVEL ROUND TABLE ON FUTURE FLAGSHIPS

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## Introduction

CNR- National Research Council of Italy supports the strategy adopted by the European Commission to promote FET flagships and sees favorably the process which will lead to the launch of two or more of them in the near future. CNR's institutes and research groups actively took part to the bottom-up consultation aimed at collecting proposals for future flagships and a coordinated internal analysis has been carried out in order to endorse few of them as of global major interest. The internal selection process has therefore led CNR to a strong endorsement on three specific cross cutting areas: **(a)** Direct Energy Conversion, **(b)** Health Care and **(c)** Robotics. Moreover, we have deeply analyzed the global landscape, in order to single out those thematic already sustained with both national and international initiatives.

- The first endorsement is for "Direct Conversion of Solar Energy: renewable and more" (with possible complementarities with "Building a Synthetic Cell") whose motivations are listed in Annex 1.
- The second is for "The future of Health Care: deep data, smart sensors, virtual patients and Internet-of-Humans" (with possible complementarities with "Biosensors for point-of-care") whose motivations are shown in Annex 2.
- The third is for "Robot Companion for Citizen ++" with the main motivations described in Annex 3.

Despite the strong interest expressed by its research groups also on environmental and cultural and nano issues, CNR identified the three above future flagships for their higher potentiality to be game changer in the industrial and economic sectors already in the mid-term.

The future flagships here proposed, feature extensive and new applications of ICT, enriching Digital Economy and Society. Moreover, CNR already plays a relevant role in the related science-driven European actions and its present involvement in these studies shows *de facto* its strong commitment to the future flagships. Furthermore the coherence among CNR competences, Italian national priorities and EU strategies establishes the necessary alignment to reach the goals set by the flagship initiatives.

## Flagship 1 - Direct Conversion of Solar Energy: renewable and more

**Direct Conversion of Solar Energy: Renewables and More**
Possibly merging: “Building a Synthetic Cell”

**What is the S&T challenge that a candidate FET-flagship should address?**

The ability to produce renewable biofuels is key to the development of a sustainable bioeconomy, mainly because it allows to maintain well established transportation technologies simply substituting fossil fuels with fuels deriving from widely available and renewable resources. An overall reduction of the environmental impact, and in particular of greenhouse gas emission, would be one of the main benefits of this transition. However, current technologies for biofuel production rely, one way or another, on the supply of biomass, a fact that sets an upper limit to the production potential. First generation biofuels derive from commodities that are also at the basis of human nutrition, such as cereal seeds. Their extensive use for biofuel production is going to compete with feed/food and energy uses, and to have a negative impact on global food and nutritional security. Second and third generation biofuels, derived from urban and agricultural wastes, dedicated non-food crops preferentially grown on marginal lands, and algae have some clear potential, but further improvements are needed to enhance yields and reduce production costs. **The identification of novel systems able to perform a direct conversion of solar energy and widely available raw materials into fuels is expected to overcome the limitations of current approaches, and would be a major breakthrough in the transition to a circular economy**.
Recent advances in science and technology have set the basis for the development of such systems.
These include tremendous progresses in analytical methods such as laser and magnetic resonance spectroscopy, synchrotron and neutron techniques, which have resolved structure and principles of operation of natural photosynthesis, and allow studying materials in devices under operation conditions. Breakthroughs in high-throughput analyses, systems biology and chemical biology make massive sequencing of taxa, species, and strains possible and have paved the way to the design of organisms with the desired properties. Yet another useful breakthrough is with computational studies, which can be helpful across the entire hierarchical system, starting with biological systems and their assembly (from genomics to phenomics), materials, components, devices, bioreactors, growth facilities, and their integration with help of smart grids in the energy society.
**Direct conversion of solar energy is an innovative approach which eliminates both fossil fuel and biomass as intermediates, with at least 70% photon to chemical product yield. Starting with water and carbon dioxide ($CO_2$) as the raw materials the aim is for an unlimited variety of (bio)chemical outputs with widespread applications, such as renewables, complex molecules, chemical feedstock, food and feed.**

In this scenario, it is clear that a major contribution could come from synthetic biology with the generation of microorganisms able to use light, water and $CO_2$ as the source for the production of fuels. Synthetic living factories and mixed systems (photovoltaic or inorganic water-splitting catalysts coupled with engineered microorganisms) could allow high conversion efficiencies and provide a reasonably cheap source of a wide range of biofuels. Similarly, recent scientific and technological advances open the possibility to develop biomimetic or nanostructured and semiconductor-based system. However, the whole field needs a major boost to bring the technology to maturity, and make it economically viable.
**Why is a Flagship necessary?**

There is an urgent need for reducing the atmospheric temperature increase through lowering emissions of carbon dioxide in the atmosphere (See Paris Agreement by COP 21). **The need of lowering CO2 emissions conflicts with the social need for more energy. Direct conversion of solar energy is an innovative approach that can solve this paradox.**

The frontier research in advanced direct conversion technology requires addressing a number of interrelated topics in the coming decade, which would enable this innovative technology to move to a more mature stage of technological development.

In the last 10 years, progress has been made in the direct conversion of solar energy to chemical energy, resulting in the production of a 'solar fuel' through the use of water as electron source and of visible light. The direct processes associated to this approach involve:

(1) Photobiological solar fuel production in green algae and/or cyanobacteria that excrete the fuel.
(2) Artificial photosynthesis in molecular systems, mimicking natural photosynthesis.
(3) Solar fuel production in nanostructured and semiconductor-based systems.

All these approaches can be considered highly interdisciplinary, requiring a continuous communication between research areas that span from life science to material science and information technology. Electrocatalysis, membrane science, thin film and photonics technology for light management, biocatalysis, semiconductor photoelectrochemistry, condensed matter physics, surface chemistry, bio-electric interfaces, genetic engineering, plant physiology, to name a few, are concerned scientific disciplines. Strong input from materials-, chemical-, Electric and mechanical engineering would be also required.
To be fully productive, such a large international effort requires a high level of coordination and a long-term commitment like the one that can be provided by a Flagship Project. Inclusion in a single project would foster interdisciplinary collaborations, avoid duplication of efforts, attract private and public interests and investments, and optimize resource use efficiency. This is particularly important also considering the time factor. **Reducing $CO_2$ emission through the use of biofuels is a goal that should be reached as soon as possible, and the Flagship Project structure is certainly best suited to concentrate and optimize efforts in this directions**. It should also be considered that the Flagship Project is likely to stimulate the development of satellite international and national projects (some already active), which could further contribute to shorten the time required to reach the goal of developing a set of economically viable biofuel production systems and thus reduce greenhouse gas emissions.

**Why is it good for Europe?**

**The energy question is becoming more pressing than ever**, and Europe depends on the import of foreign-based energy, fossil and biomass**. It is the right time to prepare for, and explore, an overall "energy change"**. The progress in artificial photosynthesis such as solar water splitting or $CO_2$ reduction has been tremendous in the last 10 years, as far as materials research is concerned. Progress in device manufacture is lacking, or lying behind, but there are now scattered efforts addressing this. The field as such has developed a very good momentum across various communities, which should be conserved and streamlined before the momentum fades away. Similar arguments hold for designer organisms, where European scientists believe it will increasingly be possible to design organisms with the desired properties for consequent pipelining development of mass cultures.
Many European researchers and research institutions, including the two (University of Leiden, NL and CNR-IT) leading the proposal under the umbrella of former ESF programmes, hold prominent scientific capacity in the field. **The development of a Flagship on Direct Conversion would reinforce Europe into a leading position in the areas (among the others) of Clean Energy, Smart Cities, Green Chemistry, resilience to Global Change, setting the benchmark for developing solutions compliant with the outcome of the recent COP 21 Meeting and the Kyoto Protocol.**

There is also a strong relation between global warming and shortage of food in the Middle East and Africa, resolving this by direct conversion is of strong interest to the European societies.

**What would it take to do it?**

The scale of the **effort required to reach the objectives is pan-European and it will optimally take 15 years**: Developing the new flagship (preparatory phase) 2016-2019; Implementation (2020-2030), 10 years since completion of preparatory phase.
Human capital involved should also be substantial. **We need a "1000 brains&hands" in Europe to forge technologies such as artificial photosynthesis and designer phototrophs that can be integrated in the built environment, landscape or sea in a reliable, safe and economic way.** We need additional efforts to join,

blend, and merge these forces together to contribute to the energy society. A portion of 10% to 30% of the thousands are in charge of organizing the efforts in an engineered hierarchical way to assure that proper communication is done among the research units and provide educational activities to raise awareness and reflection with the general public. This includes also the establishment of suited feedback protocols so warranting a continuous dynamic innovation cycle between concepts, materials, components, devices, organisms and integration into the environment. Europe has a wealth of expertise and experts in all the necessary sub-disciplines that is competitive on a global scale. The private sector (chemical, in particular), in Europe is engaging in the industrial research closer to applications presented here. There is an increasing interest in European knowledge from the energy, chemical and other sectors in Europe, in the US and in the Middle East.

**Europe is well positioned in terms of skills/expertise, capabilities, including industrial, and to address the challenge of direct conversion and exploit results** with the polar region as the primary sentinel on mitigation of global change. The research communities on solar fuels, molecular and metabolic bases of autotrophic productivity (energy and agriculture), and atmospheric research (also serving as primary users people interested in environmental consequences of direct conversion for mitigating the effects of direct conversion on global change) have expressed their interest.
EPSO, the European Plant Science Organisation, an independent academic organisation that represents more than 220 research institutes, departments and universities from 28 European countries, Australia, Japan and New Zealand, and 3.300 individuals Personal Members, representing over 28 000 people working in plant science (www.epsoweb.org) has a specific interests – among the others - toward energy crops, renewable bioresources, and green bioactive molecules, and will be a main stakeholder on the programme.
The initiative naturally emerges from two Eurocores programs, EuroSolarFuel
http://www.esf.org/coordinating-research/eurocores/programmes/eurosolarfuels.html
and MoMeVIP, http://www.esf.org/coordinating-research/eurocores/programmes/eurovol.html.

**What could be the role of ICT in addressing the challenge?**

The main goal of synthetic biology is to engineer biological systems to obtain the desired output. As such, synthetic biology is a synthesis of molecular biology, biotechnology, chemistry, information technology and engineering. **ICT has already played a major role in the development of the technologies that are at the base of the synthetic biology approach**. The study of metabolic networks, regulatory circuits, macromolecule structure and genome analysis have all taken advantage of the recent increases in computing capability. **Our understanding of biological systems can now be matched with existing ICT approaches to develop new biomimetic systems** that are best suited for specific purposes, such as biofuel production. Expanding knowledge of nanotechnologies, and their materials (also cross-fertilizing with existing Flagship Projects, namely Graphene) will further drive advances in about every field involved with direct conversion of energy, e.g. including engineering nanoscale photon transport for direct conversion. Finally, extreme computing for big data analysis have significant links to the main themes of Direct Conversion and can be found under Global Agricultural Monitoring and Early Warning, Global Carbon Observation and Analysis System, EO data and renewable energies and the GEO Global Ecosystem Initiative. In all cases, ICT will have a central role in the validation of effects of direct conversion and its potential for systemic change.

## Flagship 2 - The future of Health Care: deep data, smart sensors, virtual patients and Internet-of-Humans

**The Future of Health Care: deep data, smart sensors, virtual patients and the Internet-of-Humans**
Possibly merging "Biosensors for point of care"

**What is the grand S&T challenge that a candidate FET-flagship should address?**

Our individual existence and well-being depend primarily on remaining healthy and during ill health, receiving the individualized, optimal therapy. The continuing 'health' of our societies is, in contrast, increasingly threatened by the enormous cost of providing appropriate healthcare (currently 4 billion euros PER DAY in Europe alone) in the rapidly ageing societies of Europe. When faced with similar challenges with harmful and/or expensive consequences in other areas we have followed a very simple principle: mistakes are unavoidable in dealing with highly complex processes. While we cannot avoid making these mistakes, we can avoid most or all of their consequences by making these mistakes in-silico. This change of strategy has been implemented in most areas of our existence, increasing efficiency, saving lives and reducing costs.

This enormous progress has, as yet, reached neither our health care system nor the way we develop new drugs. Drug based therapy and prevention is still statistical, with many patients receiving drugs, which are ineffective or, even worse, harmful. Unavoidable errors in drug development still cause the cost per drug reaching the market to remain in the multi-billion euro range and endanger patients participating in large, non-stratified clinical trials. In addition, our 'health' care system is still far too much a 'disease' care system. The majority of our efforts are focused on treating rather than preventing diseases; or at least diagnosing diseases (or their progression) early enough to be able to react.

Changing this will require nothing less than a revolution, based on technical developments in two general areas, but intimately linked to many other aspects of the organization of health care and its legal and regulatory basis (see also www.healthcarecompacteurope.eu):

We need to know much more about the patient (or the potential patient), based on advanced -omics (e.g. genomics, proteomics, metabolomics) analyses, imaging techniques, and information from sensors deployed in various form factors. We will draw primarily on concepts developed under two separate Flagship proposals (both of which had reached the final stage of the last competition): IT Future of Medicine (ITFoM: www.itfom.eu), with a very strong -omics component, and 'Guardian Angels for a Smarter Life' (www.ga-project.eu/), with a particular focus on the development of novel autonomous sensors/low energy computing. In addition, we plan to incorporate a similarly strong imaging component, from the level of individual cells up to the entire organism.

Data is however not everything. We also need concepts to integrate this information and to predict the effects and side effects of possible therapies (or preventive measures) on every individual. Towards this we will build on the concept of the 'virtual patient/virtual individual', proposed in ITFoM. Such a 'virtual twin', updated intermittently by medical/omics/imaging information, and essentially continuously by a multitude of sensors could, in theory, accompany every European through life as a true 'Guardian Angel'. These 'Guardian Angel' models will, to a large extent, be based on modelling the biology of every patient and the diseases mechanistically, providing by far the best chance to translate complex data sets into accurate predictions, complemented by machine learning/statistical techniques, whenever mechanistic models cannot be established due to insufficient knowledge, e.g. on disease mechanisms. Development in these areas will however also help to accelerate and de-risk the development of new drugs, based e.g. on virtual 'clinical trials', starting shortly after (and maybe even before) the synthesis of new candidate compounds, in a 'virtualization' of drug development matching the enormous positive effects that a similar virtualization has had on e.g. the car industry.

Technology is however only a part of the solution. We will, in addition, have to reconsider many aspects of our health care system, its legal basis, regulations and reimbursement mechanisms, to draw maximal benefits from the significant progress in technologies allowing us to truly personalize medicine and prevention. We propose a vision of a truly individualized health care and disease prevention system in Europe, based on a detailed characterization (e.g. clinical, molecular, imaging and sensor based) of the patient/individual and their wellness, health and disease course, **exploiting the most advanced molecular, imaging, sensing, computing and communication technologies, through an internet-of-humans, for truly personalized and preventive medicine.**

The main objectives are:

- To develop the **technology, the required infrastructure, and the legal, regulatory and educational environment for a fully sustainable health care system** that will offer truly personalized medicine, prevention and wellness for European citizens, providing a completely new Quality-of-Life.
- To develop **novel -omics, imaging** and **multi-level advanced smart sensor technologies** and **big data/deep data analytics** for problem solving in IoH/personalized health care.
- To address the **full value chain of the virtual human** at all multidisciplinary levels required, from -omics, imaging and sensor data to complex simulation models.

**Why a flagship is necessary?**

Moving from the present model to a personalized health care approach poses enormous challenges to our society in terms of technology, organization and data storage/handling. This revolution will require the massive application of the novel “omics” techniques (genomics, proteomics, metabolomics), imaging techniques and personalized sensors. Concrete results cannot be achieved at national level but it requires joint pan-European efforts and trans-national cooperation.

Medicine and prevention have historically been statistical, treating individuals as members of (usually quite heterogeneous) groups. To switch focus from the statistically best therapy for billions to the individual, will ultimately require much more information on EVERY patient, than we had on the whole of human biology just a short time ago. We go from bytes to terabytes, from handwritten notes to a deep -omics characterization, from a cursory check at irregular doctor visits to continuous monitoring of all relevant parameters throughout life.

Our vision is a game changer, of a future in which no patient will ever again receive harmful therapies, flagged by observing negative effects first on the *in-silico* model of the individual patient. This will:

- Directly address the enormous (and almost certainly irreducible) **complexity of the biological differences between every patient and every disease by deep clinical, molecular and imaging analyses.**
- Provide a **new generation of frictionless autonomous smart sensors at all levels** required by health care data collection: implantable, wearable, environmental. Develop new feedback-interfaces for life-style feedback loops and related diseases.
- Develop **computer models of every patient and disease state** that allow physicians **to test the consequences of all possible therapies/preventative and life style measures in a virtual rather than the real patient**, computational ‘Guardian Angels’ potentially guarding every European from before birth into old age.
- **Acquire, store and redistribute the ever-accumulating amounts of data** per patient required to fulfil this goal, within a strong governance framework which protects personal data from misuse and ensures privacy.

**Why is it good for Europe?**

The health care 'Internet-of-Things' market segment is poised to hit $117 billion by 2020 (MarketResearch.com), with exponential increases in revenues predicted. The current Flagship initiative will progress beyond these projections, by generating unexpected and still unknown applications that are beyond the imagination of today's Internet-of-Healthcare. Truly personalized prevention and therapy will provide much better health at a much lower cost. The technologies which will be developed within this project do however extend far beyond health applications and into the wellness/social interaction domain, which has already generated some of the largest companies worldwide.

Poised at the interface between medical sciences, math, computation and engineering, the initiative is intrinsically multidisciplinary, fueling innovation and driving change within the field of translational medicine. We foresee and advocate innovation via a multidisciplinary and holistic vision of convergent technologies designed by doctors, scientists, mathematicians and engineers, e.g. in the form of Technological Hospitals in Europe, as a unique environment to generate innovative ideas and new services for health care.

A data and computational model driven strategy in health and wellness will provide major benefits to the region's citizens within one of the most important aspects of their lives – health care. Through the deployment of personalized medicine, prevention and wellness strategies proposed by this program and the incentives provided for European companies to form, develop and prosper as part of the new ecosystem created, there is huge potential to alleviate the suffering and improve the health and wellbeing of the EU's 500 million citizens, whilst strengthening the economic outlook of Europe as a whole.

Key Benefits for:

- **EU citizens**, through a radical improvement of their health care and a new quality of life.
- **European economy**, through new job and employment opportunities. Formation of a new vibrant economic ecosystem bridging traditional engineering, computer sciences and health care.
- **European industry**, stimulating the life sciences, pharmaceutical, health care, sensor and IT sectors, providing a large potential for innovation that can be further exploited in translational medicine.
- **Public finances,** by curbing the uncontrolled increase in health care spending (potential savings of hundreds of billions of euros) through a data and model driven truly personalized health care, improving continuously in a self-learning system, duplicating, in a sense, human evolution.

**What would it take to do it?**

The scale of effort is of the order of 10-15 years, with ambitious but practical goals, which will be addressed in a series of 'working prototypes' until final rollout of a system ready to be implemented for multiple disease areas on large scale in European health care systems. The effort is well balanced between: (i) deep -omics and imaging technologies, data analysis (ii) smart sensing technologies, energy efficient computing, big data analytics for IoH, (iii) data integration, virtual patient models and (iv) personalized medicine validations and field trials.

There are four major phases for development:

**Phase I**: **Initiation**.
Initial infrastructure development, development of improved pipelines for omics and imaging data integration in virtual patient models, implantable or wearable sensor solutions, pilot projects in oncology and life-style related diseases (e.g. Type II Diabetes).
**Phase II**: **Expansion and Consolidation**.
Development of virtual patient/virtual individual models for the vast majority of multi-factorial, non-infectious diseases, integrating -omics, imaging and sensor data.

**Phase III: Maturation and Innovation penetration**.
Scale out and clinical engagement across Europe by full adoption of the new methods and innovation by technology-health care interactions, -omics and all-scale imaging and sensing technologies, model validation and model improvements through feedback of treatment results.

**Phase IV**: **Full Implementation of paradigm shifts**.
Establishment and deployment in practicing health care systems, effect and impact of personalized and preventive medicine quantifiable.

Existing EU financing tools (e.g. Horizon2020, regional funds, Juncker Plan) will be leveraged, supplemented by private funding sources once the EU expresses its political will and creates the required legal environment. It is expected that in the later stages the private sector would top-up the EU funds at a ratio of minimally 1:5 (public/private).

**What could be the role of ICT in addressing the challenge?**

This initiative is more than timely and will position Europe at the edge of advancements in diagnostic techniques (-omics, imaging, autonomous sensors) as well as translational and personalized medicine. Within the field of Information and Communications Technology (ICT), Europe has an important role to play in Embedded Systems as part of future IoE and Cyberphysical systems. The health care, automobile and aeronautical industries are key for European leadership; however, the role of new smart sensing technologies for health care is seen as much more revolutionary due to the significant societal impact and through the direct connection to a more sustainable model for health care costs. It will therefore be important to further develop the fundamental infrastructure that will enable scientific discovery and progress, in tandem with the political mechanisms in Europe that will support the translation of innovation. This will not only ensure maximal benefits for European citizens through improvements in the health care system but also provide economic benefits due to the development of a vibrant economy that links medicine, diagnostics and IT.

Particular attention will be given to the following areas:

- **Clinical/imaging/molecular survey** (genome, epigenome, transcriptome, proteome, metabolome, immune status etc.) techniques to provide a detailed characterization of individuals in health and disease.
- **New self-powered families of revolutionary sensors for IoH/truly personalized health care** based on **energy efficient approaches** and **heterogeneous integration** solutions in bio-compatible form factors to extend human senses and to support specific prevention strategies.
- **Self-learning mechanistic/machine learning models** translating this information into predictions on the future development of diseases (prevention) and the likely response to specific therapies and preventive measures.
- **Data security and availability:** hardware to software solutions specific for IoH/personalized medicine data. New human-machine interfaces for IoH/personalized medicine, personalized and capable of non-verbal interactions.

The aims and goals of the proposal will also align with the *Health Care Compact for Europe* (www.healthcarecompactforeurope.eu), an international initiative that promotes the use of a data and computational model-driven approach to sustainable health care.

The project will also actively leverage synergies between similar initiatives worldwide, including the 100K Wellness Project (http://research.systemsbiology.net/100k/), the Personal Genomes Project (PGP, www.personalgenomes.org/), the new Precision Medicine Initiative (http://www.nih.gov/precisionmedicine/) by the US government; for smart sensing technology, road-mapping links for analytical techniques are foreseen with the recent NEREID initiative (www.nereid-h2020.eu/) and with existing activities in the Joint Undertaking ECSEL (www.ecsel-ju.eu/).

## Flagship 3 - Robot Companion for Citizen ++

### 1. What is the S&T challenge that a candidate FET-Flagship should address?

Robot Companion, the robot of the future, will assist and go with humans in all daily life and work. It will be companion of humans both when it will directly interact with them and when it will solve autonomously (or semi-autonomously) operations to relieve humans from demanding and risky operations. Although it is already possible to encounter embryonic and scattered examples of some of the Robot Companion functionalities in cutting edge technologies, the Robot Companion is a grand challenge that needs step-changes in many different disciplines[1] and it needs the foundation of a new approach to robotics.

Today, conventional robotics based on the mechatronic paradigm reveals its limitations when more complex less structured environments and task sets are considered for applications, thus likely preventing a universal use of robotic systems in natural (e.g. outdoor ground, underwater, space) and/or human populated sites (e.g. shops, public services, factories, etc.). For instance, system complexity increases with functions, leading to more than linearly increasing costs and power consumption and decreasing robustness while increasing application-related uncertainty.

The challenge here is twofold: on the one hand, compliant hardware and “soft” robotics solutions must be devised to deal with unstructured environments and improve safety of machines working in close collaboration with humans (be they co-workers, users or external actors). On the other hand, complex cognitive abilities are required to make sense of the world, deal with high uncertainty and seamlessly interact with others. Both the robotics hardware and cognition need to be dealt with in an integrated, systemic way, due to the high interrelation between the two.

In order to address the challenges of Robot Companion, it is necessary to pursue a radically novel biomimetic paradigm, grounded in the scientific studies of intelligence in life, exploiting interdisciplinary research in robotics, AI, cognitive sciences, and biology. This approach will lead to a new understanding of the brain-body nexus in the natural environment thus leading to robots of novel intelligence, capabilities, adaptivity and robustness. A radically new bodyware, exploiting compliance instead of fighting it, will be integrated with ideas as “morphological computation”, “simplexity”, evolutionary and developmental approaches, thus exploring and exploiting the possibilities offered by the general paradigm of “embodied intelligence”. Moreover, suitable cognitive architectures, taking into account robot's physiological demands, as well as environmental and social influences, will bridge the gap between embodied intelligence and the high level behavior of robotic systems in more complex applications where the interaction with humans are fundamental.

The result will be a new generation of robotic systems able to achieve complex functionalities with limited resources and energy usage with cheap, fast and effective control and computing. This “game-changer” technology, will enable the development of smart systems such as co-worker robots (in factories, services, and underwater), nurse and surgeon robots, reconfigurable architectural and urban active spaces, farming and fish farming robots, bird-like flying drones and exoskeletons. The impact on many areas of human living, such as medical and social services, manufacturing, agriculture, entertainment, humanities and the arts, will be tremendous. Potentially soft animal-like intelligent robots will be able to perform any (non creative) activity now executed by human beings. Expected outcomes of such an initiative will be self-organizing emerging orchestration controls methods, new soft materials with distributed intelligence, sensing and actuation and so on and so forth.

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[1] Such as, but not limited to, AI, sensors, material, actuations, planning, scheduling, applied mathematics, data mining, IoT, control, design, awareness, cognitive sciences, computer science, computational power, *etc*

With respect to the current paradigm, Rethinking robotics for the Future Robot Companion will address a revolution at a number of different levels:

**A) Mechatronic paradigm in Robotics**

The complete cycle of design and production of robots needs disruptive innovations in the fields of:

(1) Modular robots, *i.e.*, robots with dimension, installed power, actuators typology, control properties, cooperative modality that can be easily reconfigurable according to the application. Modular robotics enables the mass introduction of assistive robots in factories, of personal robots in daily activities, of autonomous and collaborative service robots in frontiers activities, *etc.* Modular robotics will introduce innovative design paradigm in order break common division between industrial, personal, service, aerial, underwater robotics.

(2) Wearable Robotics, *i.e.*, empowering machines for humans, will be instrument to enable human in high demanding environments like space or underwater scenarios and to preserve and improve the factory productivity in the aging society. Wearable robotics will be instruments to dramatically improve the quality of life of humans with disabilities or to support the elderly in the daily activities

(3) High-Payload Collaborative robots, *i.e.*, in order to make robots a pervasive technologies in production system and outdoor applications physical robot-human interaction will have to be guaranteed regardless the robot payload and dimensions. Humans will have to safely interact with high-payloads robots as well as with lightweight robots.

**B) Robotic System Embodied Intelligence**

(4) Human-Centered Systems, *i.e.*, robotics will be the enabling technology to rethink the industrial and service activities. Industrial and service robots will require embodied intelligence completely interconnected with all the elements of the overall system. The human becomes part of the cyber-physical words, i.e. cyber-human models are introduced. The grand challenge is to completely relieve humans from robot-like tasks and empower humans with truly high added-value tasks. Concurrently, robots should reach a human-like level of cooperation in: i) perception of environment and perception of tasks; ii) multi-modal communication channels; and iii) transparency and adaptation: human react swift (and emotional) reactions to coworkers, changing assignments, fixing errors, reacting to misbehaviors, *etc*.

(5) Multi-agent Robotics, *i.e*., the use of multiple, possibly different, robots for performing complex tasks, nowadays concurrently executed by tens of persons. From mathematical foundations, like consensus control approaches derived by the game theory, novel approaches are needed to address multi-agent kinodynamic motion planning problems that provide also (re)configuration of the multirobot applications. The multi-agent robotics will be a pervasive enabling technology in factories and in highly changeable and unstructured scenarios, like, e.g., outdoors and underwater,

**C) Sharing Robotics Knowledge**

(6) Social acceptance of industrial robots. The presence of truly collaborative robots in industrial and service domains is somehow limited by “soft” barriers, including, but not limited to lack of widespread knowledge of technology, little customization of robot applications by the actual end user, lack of natural interaction with robots. Most of such limitations are underestimated by a research community suffering a “technology-push” bias, which does not reflect the relative low rate of robot usage by followers and laggards. Perception and social acceptance of robots in everyday work life, as companions and coworker rather than job killers, is still a major societal challenge for the general population.

(7) WWW of robots. Distributed knowledge and global experience through the WWW of robots, able to share production experiences and configurations. Based on the IoT paradigms, robots would be able to search for solutions to unexpected problems and events on the basis of past experience.

**2. Why a Flagship is necessary?**

The S&T need of a novel interdisciplinary paradigm to tackle the main technical bottlenecks to the full exploitation of robotic technology in less structured environments with strict cooperation and interaction with humans requires the development of a novel interdisciplinary paradigm through the construction of an interdisciplinary community beyond Robotics and AI by means of structured large-scale cooperation at the European level. Many disciplines, such as (but not limited to) AI, robotics, machine learning and big data, cyber-physical systems, control theory, sensors, IoT, self-organizing networking, ontology and cognitive techniques, applied mathematics, material science, biologists, neuroscientists, economists, etc., will have to cooperate for the design of the Robot Companion. A strong and well-organized coordination of efforts to achieve this ambitious goal can be allowed by the proposed new FET-F initiative on Robotics. The Robotics Companion is not only a new disruptive machine but it will be the pivot technology to rethink the industrial and service systems of the future. Humans will be the center: the human work will be eased by robots, and the robots will be enslaved to human wishes, needs, intensions and state. The systems will have to automatically interpret, understand and react to human actions and behavior, also without direct verbal communication.

The proposed FET-F initiative on Robotics will federate existing initiatives on Robotics funded by Member States, Regions, funding agencies, industries, sharing the proposed unifying grand vision, and leading to a synergistic agenda, with a multiplier effect. Such federation will have the potential to leverage other relevant initiatives even from non-EU Countries and to develop a long-lasting coordination of pan-European and international research efforts.
It would actively participate and connect with the high-quality and extensive research initiatives already dedicated to Robotics within EU frameworks (i.e., H2020), with SPARC and with the many robotics-related projects at EU, National and Regional levels in order to reduce duplications to a minimum, and to rather keep and foster synergies.
In conclusion, a FET-F program on Robotics will allow Europe to keep and expand its leadership in Robotics and in high added value mechatronics products by focusing and exploring the potential of science-based disruptive innovations, thus protecting and improving its prosperity in the coming decades.

**3. Why it is good for Europe?**

In order to guarantee the future quality of life and prosperity of EU citizens, it is necessary a dramatic increase of productivity and technological capabilities compatible with the conservation and protection of natural ecosystems and sustainable exploitation of natural resources. Europe has a longstanding tradition in robotics research, and hosts some world leading actors in industrial robotics. Moreover, Europe has an internationally leading position in Cognitive and Adaptive Robotics also thanks to the large number of high quality research projects that have been founded by the EU within the Cognitive System and Robotics and the Future and Emerging Technologies initiatives in the last decades. On this basis, Robotics and AI are seen as possible bricks of the solutions. In fact, with their increased awareness and ease of use, robots represent the dawn of a new era, ubiquitous helpers improving competitiveness and our quality of life. Robotics is set to become the driving technology underpinning a whole new generation of autonomous devices and cognitive artefacts, providing the missing link between the digital and physical worlds. Yet technical and scientific limitations make difficult to hold their promises in the long run. A FET-Flagship on new paradigm robotics will contribute to address some of the challenges related to the future quality of life, security, and productivity, by contributing to remove the bottlenecks hampering medium-long term progress in robotics technologies and to define a sound ambitious research program enabling a pervasive utilization of intelligent robotics and systems technologies, as well as a fruitful integration of new generation of robots in human environments. In fact, and despite remarkable progresses in the last few years, real-world less structured environments and the complex tasks and environments of daily life activities still result extremely challenging for service robots based on the current technological and scientific paradigm. Europe can in this way be the forerunner for experimenting new models of using machines, e.g. shifting the paradigms from usage in factories to individual ownership of robots assisting in task execution.

A European initiative on deeply science-based robotics would anticipate, but at the same time connect very nicely with, similarly ambitious initiatives being planned in Japan, Korea and China.

**4. What would it take to do it?**

A 10-year ambitious and federated FET-Flagship or similar program on Robotics is needed, aiming at breaking through the scientific, technological, societal barriers still hampering the pervasive deployment of robotics solutions in the economy thus preventing the much needed unleashing of the exponential sustainable growth they promise. Specifically, *Rethinking robotics for the robot companion of the future* will assess the scope of theoretical and experimental applicability of current methods and proposed alternatives. It will comprise such actions as the involvement of a large interdisciplinary and multi-national community, focused research projects, fund raising (at national and international levels), social and industrial impact and efficient management. Special attention will be paid to the relationships with the national funding agencies (e.g., NRFOs).

It will be necessary to define, for instance:

- S&T roadmaps: the scientific contents, in terms of challenges to face, intermediate objectives, and expected results, on a timeline;
- Exploitation & Competitiveness strategy: the long-term exploitation plans for robot companions;
- ELSA framework: the ethical issues, the legal framework, the social implications (particularly those related to the issue of robots and jobs);
- Governing and finance structure: the organization and procedures for managing a FET-Flagship size project and the mechanisms for financial administration.

These long-term plans include theoretical investigations on the basic principles of robotics to allow the design of cooperative robots that can be really considered companions, as well as the design and development of core technologies and the realization of prototypes for key application scenarios. Among the planned theoretical investigations are the following:

- Theory of morphological computation. A novel theoretical framework, that encompasses mathematical descriptions of the principles that apply at each length scale, will be explored. This framework will help to develop design principles and tools, to increase our understanding of the design space, and to support the building of the theoretical basis for the principle of orchestration. Some initial steps have been taken, but much more work is needed;
- Understanding the design space and defining design principles: materials, mechanics, electronics, energy. The range of technologies suitable for developing the envisaged robots and their behavioral properties, constraints, and energetic requirements will be mapped. The role of shape, mass, and other physical properties in the integration and design process will be revisited. Evolutionary algorithms will be investigated as a tool for designing robot bodies that implement morphological computation;
- Principles of orchestration and control methods in soft, continuous, reconfigurable robots. Principles of orchestration, a novel "control" paradigm in robots, will be synthesized. The principles of orchestration will largely rely on unsupervised and distributed artificial intelligence methods, such as artificial evolution, swarm intelligence, and on neural computation. The goal will not be just to adopt those methods to implement conventional control principles, but rather to capitalize on them for emergent computation;
- Integrating suitable cognitive functionalities within the morphological computation framework in order to allow the robot to interact with humans and cooperate to accomplish complex tasks. Simplified robot's cognitive capabilities have to manage relevant human factors such as expectations, motivations, and emotions to assure "satisfying" experience.

The technologies that will be included in the long-term research are:

- Multifunctional materials. New materials based on biomimetic principles, like hierarchic structures, and with self-healing properties. Another interesting challenge is to make soft responsive materials (for example based on functional, hierarchical and/or micro & nanostructured composites) capable of working as actuators and sensors at the same time and to serve as computational resource that can be exploited in the context of control, e.g. as a pure physical feedback control loop. These new soft materials need to be developed with sufficient power density to make them practical.
- Energy issues. Energy consumption will be limited by the systematic exploitation of body dynamics, compliance, orchestrated control and new flexible materials. This approach may revolutionize the way in which future robots and also a wide class of machines will be designed in order to implement inherently ecologically sustainable systems;
- Integrated rigid-soft structures.

Priority will be given to a part of the many application scenarios for robot companions, like industry, agriculture, healthcare, services to aging well, environmental monitoring, search & rescue, underwater intervention, where current approaches show their limits.

Due attention will be paid to dissemination, education and outreach to and involvement of EU citizens, with special attention to young people and schools, and to elderly users. A large number of stakeholders (from science and technology, society, finance, politics, industry and other relevant communities) will be actively involved aiming at community and consensus building at European and international levels. Particular attention will be paid to ethical issues (including the largely debated issues on occupation) raised by the pervasive use of Robot Companions.

**5. What could be the role of ICT in addressing the challenge?**

Robotics is an inherently ICT-based activity, and many aspects of ICT research will be key in fostering the innovation in this field. The Horizon 2020 ICT Work Programme supports the will EU's strategic vision aiming at strengthening Europe's global position in the robotics market. Research in ICT and cognitive robotics are interwound, especially to what concerns computer vision, natural language processing, human-machine interfaces, knowledge representation and automatic reasoning, computational intelligence, sensors and actuators. Moreover, the Flagship can leverage several other key enabling ICT technologies. Massively learning robotic algorithms, expecially if bio-inspired (e.g., bio-morphic computing), need to benefit of complex ICT infrastructures, for example of parallel/grid computing. The development of self-adaptive robotic systems exploits several ICT technologies such as big data and data mining, self-organizing networking and communications, IoT, cyber-physical, etc. ICT communication and data management technologies can have a primary role in supporting many functions of the Robot Companion. In the Robot Companion vision, robots are autonomous interacting agents inside a complex socio-technical systems encompassing both robots and humans. Therefore, data collected by various agents and devices (including IoT) needs to be effectively distributed among these agents, such that they can extract knowledge and act based on it. On the other hand, mobile networking technologies will be fundamental, as robots and agents will be in general mobile and will communicate via wireless communications. To this end, the Robot Companion will embed distributed data management technologies, enabled by mobile networking mechanisms, that will support communication across all devices and agents, from simple IoT devices, to robots, to humans' personal devices. Moreover, the novel control schemes for modular and cooperative robots will have to be supported by distributed data management and knowledge extraction techniques – interoperable with centralized BigData infrastructures, which will enable distributed real-time decision making. This is fundamental to achieve the scalability and responsiveness required, e.g., in the most relevant industrial environments where the Robot Companion is foreseen to be used. Last, but not least, mobile networking and data management technologies will support the cognitive functions of the Robot Companion, by making sure that robots (and humans) can access the data relevant for their decisions at the right point in time.