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# *Bioengineered and Bioinspired Systems III*

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# Introduction

The world of engineered systems that will be serving humans in their activities as well as in their everyday life is required to undergo a deep improvement in terms of system complexity, miniaturization, autonomy, and degree of embedded intelligence. This challenge can only be brought to reality with a deep effort from very different scientific fields to let the various levels of expertise, competencies, and technologies, converge toward reliable and useful devices. Under this perspective, bio-inspiration has been demonstrated to be essential in building robust and efficient systems and devices that inherit their essential aspects from nature, but that are modified and engineered in order to satisfy implementation and functional constraints for efficient working. This is the wave followed by the Third Bioengineered and Bioinspired Systems conference. The technical program was conceived to offer the attendees the opportunity to share experiences in the very different scientific areas involved in the introduction of new methodologies, in the design of new sensors, actuators, and computing devices useful for the development of new bioengineered and bioinspired systems and related emerging technologies.

For these reasons, the relevant topics of the conference spanned from circuits and systems for cell analysis, to biosensors, biosignal processing, and biomedical applications. A new topic introduced within the conference areas was biorobotics, perception and cognition. All these areas of scientific relevance are currently the subject of an important number of research projects funded by the European Commission as well as by other important funding research institutions all over the world. These institutions are increasingly encouraging research focused in developing new methodologies for the construction of new generations of machines able to increase the level of autonomy and decision making, by embedding a high level of "self-born" intelligence. The overall aim of the conference, as testified by the conference proceedings, was to have a whole scenario where neural information processing software and hardware techniques, joined to biochemical sensors, microfluidic devices, new materials, and neuron-inspired cognitive systems contribute to the common goal to focus toward implementation in really working micro(nano)electronics sensing/ computing/actuating devices.

The conference was organized into one single track, consisting of 10 sessions for oral presentations plus one poster session. Moreover, most of the sessions hosted a keynote presentation in order to outline some of the relevant themes in the field of bioengineered and bioinspired systems. The conference began with a session on biosignal processing. This was opened by a keynote by Prof. Tetzlaff's group from the Johann Wolfgang Goethe-University, Frankfurt, Germany. Here the problem of seizure prediction in epilepsy by using delay-type cellular

nonlinear networks processing data acquired by data acquired by multi-electrode stereoelectroencephalography (SEEG) and electrocorticography (ECoG) was carefully and clearly addressed. This lecture was followed by an interesting presentation, co-authored by outstanding researchers from the University of California, San Diego, and the John Hopkins University. Here multichannel EEG signal acquisition was faced with presenting the design of a node-based network for low-power, low-noise signal acquisition. The next session was devoted to the address event representation (AER) of information, an emergent neuromorphic communication protocol allowing real-time massive virtual connectivity. The keynote lecture dealt with an interesting methodology based on implementing a wireless AER for integrate-and-fire neurons applied to close proximity biological sensors. The second speech addressed the problem of communicating several AER-based chips to compose a powerful processing system based on FPGAs. The last paper concerned the application of AER for artificial vision to code pixel intensity through spike sequences; several image filtering algorithms were presented.

The third session was dedicated to bioinspired architectures for perception and cognition. The session opened with a keynote by the University of Bielefeld biological cybernetics group who proposed a new methodology implemented on a robot model of a stick insect, and dealing with a mental model expressing emergent cognitive skills viewed as the capability of planning ahead to overcome critical situation encountered during locomotion in uneven terrains. Subsequently a new methodology based on the winnerless competition principle, was applied to implement perception skills in roving robots. The fourth session dealt with circuits and systems for biomedical applications. A research group from the University of Limerick regarded the problem of tracking the real-time positions of a diagnostic capsule in the gastrointestinal tract, where a RF signal and some interesting algorithms were employed to determine the approximate position of the capsule location. Another interesting contribution, presented by a joint research group from IMSE-CNM-CSIC in Seville and the University of Malaga, dealt with integrated circuit interfaces for artificial skin. Artificial skin is a smart array of pressure sensors and, as in the case of artificial retinae, involves a huge amount of signals to be concurrently processed to extract useful information. A real advantage involves the increase of the amount of signal processing at the sensor level. In the manuscript, a voltage to frequency approach is proposed as front end interface for an analog piezoresistive tactile sensor.

A session on bioinspired circuits and systems contained a contribution by the University of Jena (Germany) on a massively parallel VLSI architecture useful for future smart CMOS cameras based on emergent bioinspired computing paradigms. Another paper in the session reported on detained studies on the retina modeling and simulation, verifying many complex phenomena in visual processing and in particular in motion detection. A third paper dealt with new adaptive flow sensor arrays inspired to the mechanosensors in crickets.

Two sessions were devoted to biorobotics and dealt with different approaches covering different aspects of this scientific field, from the design, realization, and optimization of bioinspired walking robots and related control algorithms, to new learning algorithms for self-learning navigation control.

Another interesting session dealt with circuits and devices for cell analysis. The session contained a manuscript on the design of microelectrode arrays for tumor cell separation and detection, and two papers on microfluidic devices for the analysis of cells and for real-time monitoring of microfluidic phenomena, for example in microcirculation. The last two sessions were devoted to biosensors and devices and to smart materials for biomedicine. They contained interesting contributions on these hot topics, among which one, presented by a research group from the Univ. de Barcelona, dealt with the laser-induced forward transfer technique for biosensor preparation. Another paper, from the Istituto per la Microelettronica e Microsistemi (Italy), presented an optimized immobilization protocol for the glucose oxidase for biosensor development on silicon substrate. An interesting contribution, from Purdue University (USA), showed the capacity of the alpha-synuclein protein to assemble into nanofibers: This can be used for the synthesis of metallic nanowires. Finally a contribution from the Ioffe Physico-Technical Institute (Russia) presented studies on structural properties of the nanoscale integrated semiconductor quantum dots conjugated with biomolecules for biomedical applications.

A poster session completed the conference: Here other interesting aspects within the topics of the conference were presented, covering both theoretical aspects and applications. The list and relevance of the manuscripts presented at the conference demonstrates the success of this initiative, useful for the contributing authors to exchange opinions and to start new scientific collaborations, and offering researchers all over the world the opportunity to keep updated in the emerging field of bioengineered and bioinspired circuits, systems, and devices through these proceedings.

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# The Nano Revolution: Bottom-up Manufacturing with Biomolecules

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## ABSTRACT

As the nano-scale becomes a focus for engineering electronic, photonic, medical, and other important devices, an unprecedented role for biomolecules is emerging to address one of the most formidable problems in nano-manufacturing: precise manipulation and organization of matter on the nano-scale. Biomolecules are a solution to this problem because they themselves are nanoscale particles with intrinsic properties that allow them to precisely self-assemble and self-organize into the amazing diversity of structures observed in nature. Indeed, there is ample evidence that the combination of molecular recognition and self-assembly combined with mutation, selection, and replication have the potential to create structures that could truly revolutionize manufacturing processes in many sectors of industry. Genetically engineered biomolecules are already being used to make the next generation of nano-scale templates, nano-detailed masks, and molecular scaffolds for the future manufacturing of electronic devices, medical diagnostic tools, and chemical engineering interfaces. Here we present an example of this type of technology by showing how a protein can be genetically modified to form a new structure and coated with metal to lead the way to producing "nano-wires," which may ultimately become the basis for self-assembled circuitry.

**Keywords:** Nanotechnology, biomolecule, chaperonin, self-assembly, nanowire

## 1. INTRODUCTION

The controlled organization of materials on the nanoscale is the ultimate goal of the bottom-up manufacturing pursued by nanotechnology. At this scale, material packing densities and manipulations present technical challenges for current patterning manufacturing technologies, such as dip-pen and electron and ion beams lithography. While this scale exceeds the limits of most lithographic patterning processes, packing densities and quantum effects (e.g., single electron tunneling quantum confinement) are strong incentives to pursue this miniaturization process to nanometer size scales. The alternative approach that is widely being pursued involves self-assembly and self-organization.

Self-assembled inorganic and organic molecules that naturally form one-, two- and three- dimensional structures are a major focus of research in nanotechnology. One- and two-dimensional nano-structured materials are being investigated for their use as templates, scaffolds, or guides for fabricating prototype devices, such as quantum-dot lasers (1), single-electron transistors (2), memory units (3), sensors (4), optical detectors (5), and light-emitting diodes (LEDs) (6). There is currently also a growing interest in fabricating one-dimensional (1D) nanostructures from metal or semi-conducting materials, which can be used as both interconnects and functional units in electronic, electrochemical, and electromechanical nano-devices (7). Efforts to fabricate such nano-wires and nano-tubes include using inorganic templates, which take advantage of step edges of solid substrates, and organic templates, which take advantage of self-assembling polymers, including synthetic polymers and biological macromolecules, including DNA and proteins.

Biomolecules in general and proteins in particular, are not only capable of self-assembling into intricate patterns with nanoscale architecture, they can be manipulated and functionalized using methods developed for biotechnology. The astonishing diversity of structures formed by proteins is apparent in nature. Because their synthesis is genetically directed, both their structure and their function can be effectively manipulated. DNA and various proteins have already been used as templates for nanowires and nanotubes that have been incorporated into nano-structured materials and devices (8-14). We are exploring potential nanotechnology applications for a class of 60 kDa proteins, known as Hsp60s.

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### 1.1 Obtaining the protein building blocks

The HSP60s are proteins that in the presence of ATP/Mg self-assemble into regular double-ring structures known as "chaperonins." In nature, chaperonins are ubiquitous and essential biological structures comprised of 14-, 16-, or 18-HSP60 subunits arranged as two stacked rings forming supramolecular structures 16 to 18 nm high and 15 to 17 nm wide, depending on their species of origin. The HSP60-subunits consist of three structural domains named in accordance with their position in the double ring. The equatorial domain is the interface between the two rings and includes an ATP binding site that affects changes in the overall conformation of the double ring. ATP binding causes shift in the apical domain by a shift in the intermediate domain, hence the name "hinge domain".

We used the chaperonin with 18 subunits produced by *Sulfolobus shibatae,* an organism which lives in geothermal hot-springs and grows optimally at temperatures of 83°C and at pH 2.0 (15). This organism makes three related Hsp60 subunits and we chose the subunit called "beta." Sequence and structural information are available for beta and we have previously established that it forms octadecameric chaperonins (9-subunits/ring) that can be induced to assemble into filaments (16). Expressing the thermostable beta subunit in *Escherichia coli* allowed us to eliminate most *E. coli* proteins, which are thermolabile, simply by heating total protein extracts (17). A structure for the wild-type beta-chaperonin was constructed by homology modeling using the X-ray structure of the isomorphic chaperonins (18). The structure was used as a guide for mutagenesis to modifying beta to produce chaperonins that can be used for patterning (19). In previous experiments, we have demonstrated that the beta subunits retain their ability to form chaperonin double rings even after their ends are moved to a variety of new locations in the protein (20). This process called, circular permutation, allowed us to explore the effects of truncating the beta subunit.

## 2. MATERIALS AND METHODS

### 2.1 Cloning and expression of the dwarf protein

Gene construct and cloning of the dwarf protein are based on the procedures of circular permutation of the chaperonin protein Beta (20). Fragments of DNA before and after the permutation site are amplified separately using the PCR method with the flexible linker with the sequence GGSGGT added to the beginning and end of the genes. The two fragments are annealed together at the flexible linker and the resulting template DNA was cloned into a standard *E. coli* expression plasmid (pET19b, Novagen) (21). The protein was expressed from this plasmid in *E. coli* BL21DE3 and purified by heat treatment and ion exchange chromatography using Mono-Q column.

### 2.2 Assembly of the dwarf protein into rings, filaments and 2D arrays

Subunits of the dwarf protein in HEPES buffer were mixed with NaCl, $MgCl_2$, and ATP and the final concentrations are 1-5 mg/ml, 0.1 M, 25 mM, and 1mM, respectively. The mixtures were incubated at 4 °C - 90 °C for 1 hour; rings or filaments or 2D arrays were formed depending on temperatures.

### 2.3 Nickel deposition of dwarf filaments

The procedure of electroless metal plating (22) was followed with a minor modification. Dwarf filaments, 100 μL, in 25 mM of HEPES buffer pH 7.5 and $Pd(CH_3COO)_2$ 11 μL, 2mM were mixed and incubated at room temperature for 1 hour. The mixtures were dialyzed against MES buffer pH 5.26 at 4 °C overnight first, then against distilled water. The Pd-filaments solution was added to the metallization bath containing 4 g/l of DMAB and 200 mM of NiSO4 for 2 min to 1 hour.

### 2.4 Electron microscopy

Protein samples were attached to lacy carbon grids with ultrathin formvar (Ladd Research Industries), stained with 0.22 μm filtered 12% uranyl acetated for 3 min, rinsed with water, and air dried at room temperature. Nickel-coated protein samples were not stained with uranyl acetate. The grids were viewed in a LEO 912 AB with tungsten filament at 100 kV. Images were recorded with a MegaView digital camera using ANALYSIS 3.5 software.

### 2.5 Conductivity measurement of the protein nanowires

The conductivity of protein nanowires and nickel coated protein nanowires were measured using a HP semiconductor parameter analyzer 4155 B. The nanowires were laid on an interdigitated electrode structure (IDE) across two electrode leads by casting a droplet of aqueous solution of protein samples (23). The IDE with many pair of fingers provides a large contact area of electrode to the nanowires, which ensured that the contact between the metal electrode and protein nanowires are reliable. The measurement was done by sweeping the voltage with scan rate of 2mV/sec and recorded the current passing through these nanowires.

## 3. RESULTS

### 3.1 Truncating beta for new functions

Although a detailed 3D structure of beta is not yet known, X-ray structures for homologous chaperonin subunits are known (18, 23-26) and detailed transmission electron microscopic (TEM) and cryo-electron microscopic analyses of *Sulfolobus shibatae* chaperonin have been reported (27, 28). Using X-ray structures of homologous subunits and TEM analysis of *Sulfolobus* chaperonins, we produced a hypothetical 3D model for the beta.

To truncate the Hsp60 subunits, we began with the circular permutant of beta in which the native amino and carboxyl termini were shortened by 45 amino acids, joined by a six amino acid linker, and new termini were created at amino acid position 267 (20). The new termini of this permutant, referred to as beta-267, are in the loop region of the apical domain.

The chaperonin double rings formed by beta-267 are indistinguishable from wild-type beta rings by TEM and have nearly identical thermodynamic stability based on differential scanning calorimetry (20). Guided by structural information, we truncated beta-267 by deleting 101 amino acids from the amino-terminus of beta-267, which deleted half the apical domain, creating a mutant of 45.7 kDa, the dwarf protein (Figure 1, 2).

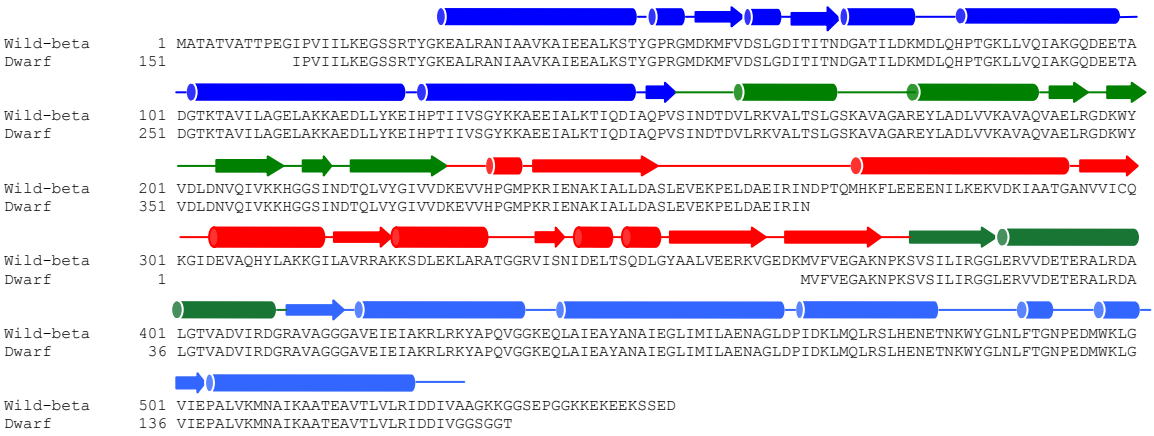


**Figure 1:** The amino-acid sequence alignments and secondary structures of the wild type beta and the dwarf mutant. The equatorial domain region is colored in blue, the intermediate domain in green, and the apical domain in red.

This dwarf subunit self-assembles into double-rings with 9 subunits per ring, like the wild-type beta from which it was derived. To produce a model of the dwarf double-ring, we used nine-fold rotational operations with a proportionally expanded diameter relative to the structure of the eight-fold rings of the thermosome. To generate the lower ring, a 2-fold rotational operation was applied to the upper ring with the rotational axis running along the center of the upper ring and perpendicular to the 9-fold rotational axis. The overall shape of the complex is an ellipsoid with a height of 12.5 nm

along the pseudo 9-fold axis and a diameter of 17 nm along the 2-fold axes (see Figure 3). The diameter of the filaments shown in the image under Scanning Electron Microscope (SEM) in Figure 3 is 17 nm and the height of the double-ring is 12.5 nm, as predicted by the models.

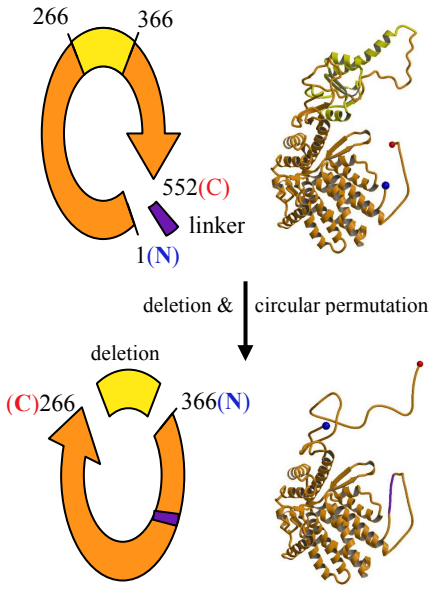


**Figure 2:** Design of the dwarf protein based on a circular permutant called beta-267 (see text for description). There are 99 amino acids (color in yellow) deleted from the apical domain of beta (top); a flexible linker consisting of the sequence GGSGGT (colored in purple) are connected to the original N- and C-termini; the new ends of the protein are now located at the cuts in the apical domain shown as blue and red balls in the dwarf protein model (bottom).

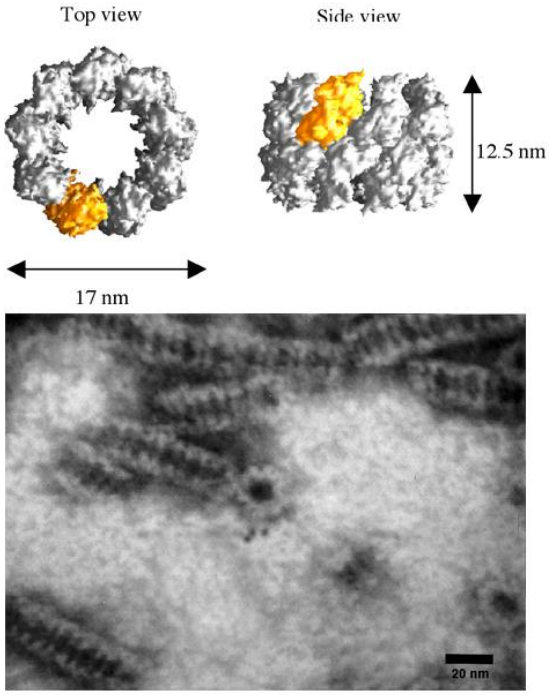


**Figure 3**: Surface representations of dwarf double-rings and SEM image of the chaperonin and the filaments it forms. The diameter of the ring is 17 nm, similar to native BETA(β); the height of the double-rings is shortened from 15.5 nm of wild type chaperonins to 12.5 nm. The SEM image shows how the rings stack through their apical domains to form filaments. Images taken at 30 kV on a Hitachi S4800 SEM courtesy of Konrad Jarausch at Hitachi High Technologies America.

### 3.2 The dwarf protein self-assemble into individual filaments or 2-dimensional arrays

We observed the double rings derived from dwarf subunits assembled into filaments, filament bundles, or 2-dimensional (2D) arrays depending on conditions. Under most circumstances, assembly required magnesium chloride ($MgCl_2$) and ATP and was influenced by temperature. The assembly rate and length of filaments was increased at higher temperatures. For example, within 30 min at 75°C most dwarf rings assembled into long individual filaments, while at room temperature they assembled into short filaments, and at 4°C they mostly remain as double-rings. Once long filaments formed, they remain intact for at least 7 days when stored at 4 °C, although were continuously released at a low rate. When incubated overnight with $MgCl_2$ and ATP, at 4° C or at room temperature there were mixtures of short filaments and 2D arrays of double rings, and a few filamentous aggregations also appeared. After overnight incubation at 75°C, we observed some of the filaments were associated with denatured proteins. Figure 4 shows images of the dwarf protein incubated at different temperatures for one hour or over night visualized by transmission electron microscopy (TEM).

In general, at temperatures between 25°C and 75°C and at concentrations above 2 mg/ml long filaments formed, ranging from 0.1 to 3 μm. The upper size limit was presumably set by mechanical forces during transferring. At temperatures >75 °C the dwarf rings and filaments denature slowly and at 90 °C the protein solution turns turbid after one hour, presumably due to protein denaturation.

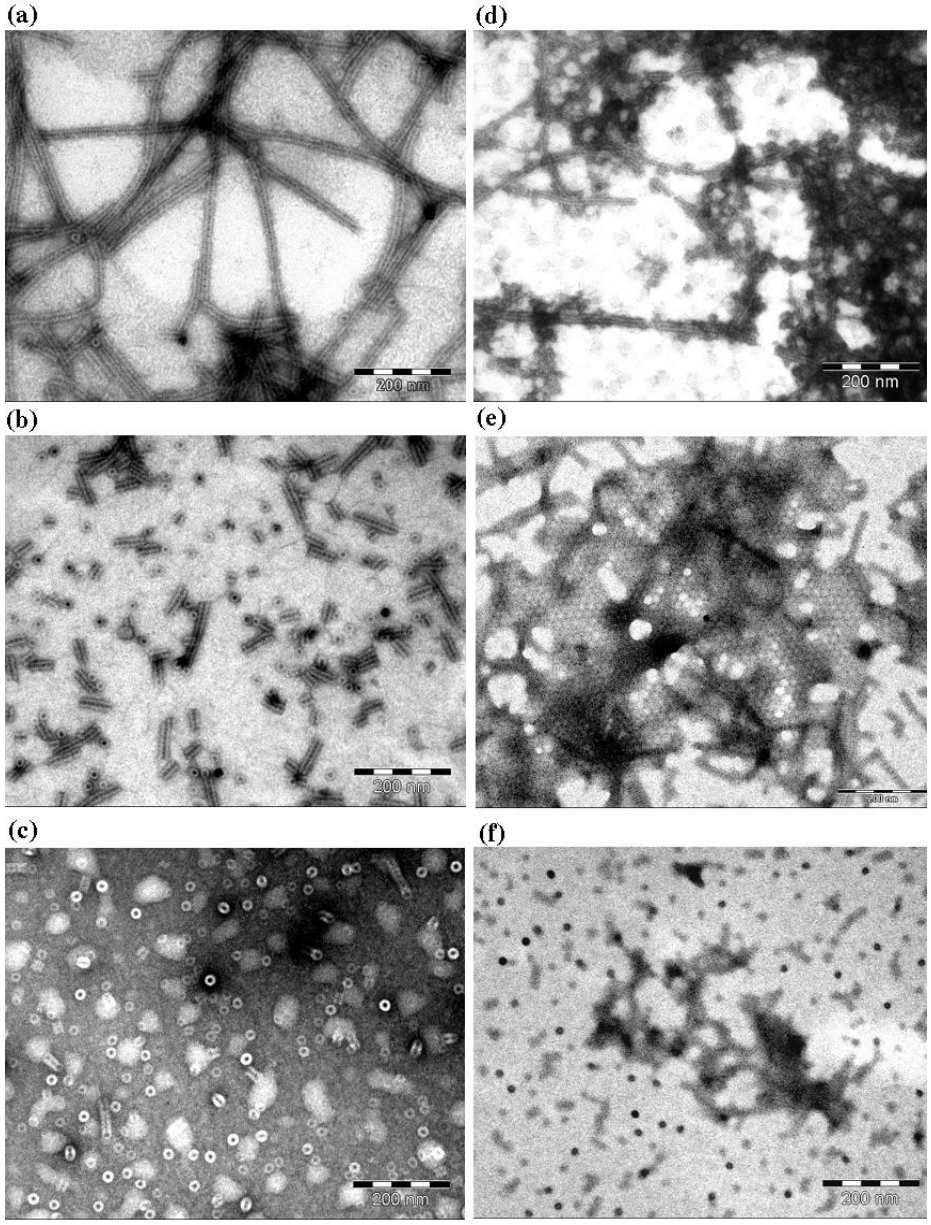


**Figure 4:** TEM images of the dwarf protein incubated with NaCl, $MgCl_2$, and ATP at different temperatures for one hour or over night. After one-hour incubation (a) at 75 °C most of the rings are incorporated into long single filaments; (b) at room temperature short filaments are assembled; (c) at 4 °C most of the proteins remain as double-rings. When incubated over night (d) at 75 °C some denatured proteins precipitate on filaments; (e) at room temperature 2D arrays are formed; (f) at 4 °C dwarf protein filamentous aggregations appear.

### 3.3 Other factors affecting filament formation

The dwarf subunit concentrations and ATP/Mg were important for both the assembly of rings and ring association into filaments. Without ATP/Mg at 4 °C or room temperature, we observed few filaments and bundles by TEM. At 75 °C after one hour, we observed mostly aggregates. At higher concentrations of dwarf subunits (> 6 mg/m), a few filaments assembled without ATP/Mg.

We also observed that dwarf subunit assembly depended on the order of addition of reagents. That is, assembly into individual filaments required that ATP/Mg was added to a mixture of protein in buffer. If the protein was added to a solution of ATP/Mg and buffer, bundles formed rather than individual filament.

We suspect that the conformation of the dwarf subunits influenced their assembly into single filaments or bundles. Studies of wild-type chaperonins have revealed two conformations referred to as "open" and "closed" (27, 29-31). In the TEM, we observed what appeared to be different conformations of the dwarf chaperonins in single filaments and bundles (Figure 5). In side views of the rings in single filaments, they appear rounded and resemble the closed conformation of the wild-type chaperonin ring, while in side views of the rings in bundles, they appear more rectangular and resemble the open conformation of the wild-type chaperonin ring. We therefore suspect that assembly into single filaments or bundles depends on the conformations of the rings: the closed rings form single filaments and the open rings form bundles. We suggest this difference in conformation influences the side-to-side interactions between rings and thereby impacts bundling.

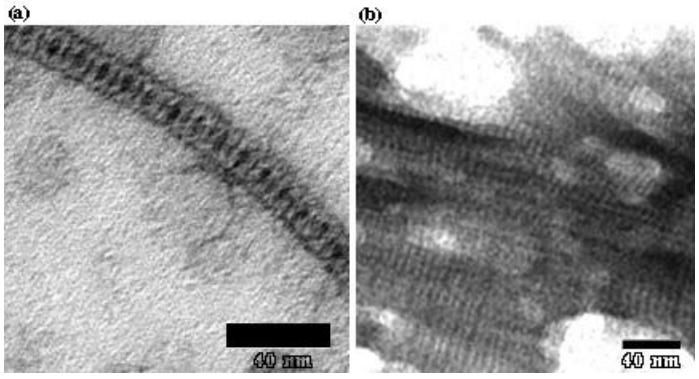


**Figure 5:** TEM images show (a) the side view of the rings in single filaments is rounded and resembles the closed conformation of the beta ring; (b) the side view of the rings in bundles is rectangle and resembles the open conformation of the beta ring.

The impact of temperature, protein concentration, ATP/Mg and subunit conformation on the formation of rings and the nature of the filaments formed by rings, require further investigation.

### 3.4 Transforming dwarf filaments into nanowires

To use chaperonin filaments as templates for creating nanowires, we used established electroless metal plating methods to deposit a thin metal film onto dwarf surfaces (22, 32). Electroless deposition occurs by a redox process in which the cation of the metal is chemically reduced on an appropriate catalytic surface. Prior to metal plating the insulating surface of the biomolecular template was activated by attaching catalytic particles. Dwarf filament surface catalysis was accomplished by adsorption of colloidal palladium salts $Pd(CH_3COO)_2$ (Figure 6). The palladium catalyst particles increased the average diameter of the dwarf filaments to approx. 24 nm (Figure 6a). Rinsed filaments with palladium nucleation sites were soaked in a solution of nickel sulfate ($NiSO_4$), with the reducing agent dimethylamine borane (DMAB). The Ni nanoparticles coalesced into a continuous metallic coating covering the dwarf filaments and increased in thickness with time. After 10 min, the average diameter of filaments was 36 nm (Figure 6b). After 15 min, the average diameter of Ni-coated filaments was 63 nm (Figure 6c). After 1 hour, the nickel particles reached a diameter of 200 to 300 nm (Figure 6d). The preferential and very regular deposition of nanoparticles observed in the presence of the dwarf filaments suggested that defined interactions between the functional groups of the protein surface and the palladium in solution were important during particle nucleation. The metallized nanowires appear aggregated and slightly bent, which is also observed on Ni-coated microtubules. The aggregation of dwarf filaments during metallization may be a result of their magnetic properties, causing attraction of the individual tubes.

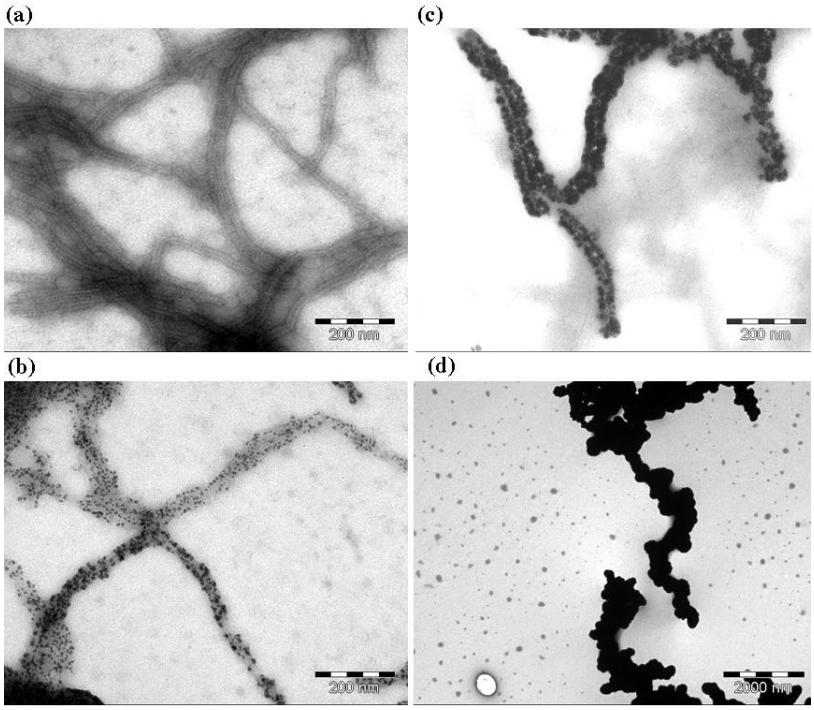


**Figure 6:** TEM micrographs showing the process of nickel coating on dwarf filaments. (a) Palladium catalyst particles are distributed over the dwarf filament surface negatively stained with 2% uranyl acetate. (b), (c), and (d) show nickel-metallized dwarf filaments resulting from DMAB reduction after 10 min, 15 min, and 1 hour, respectively.

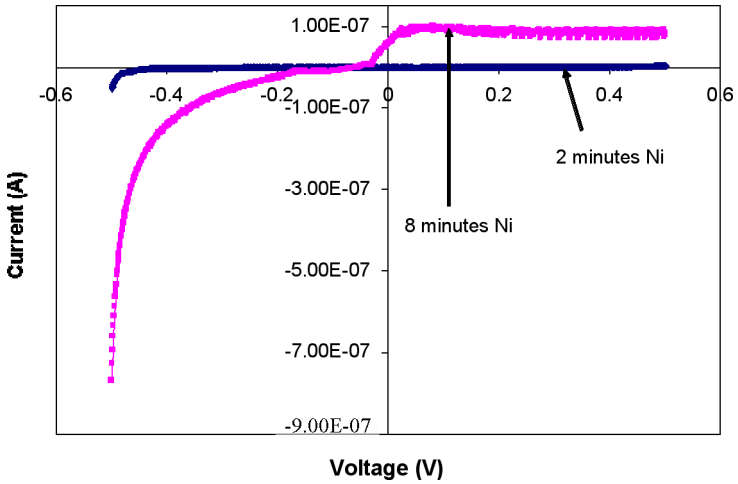


**Figure 7:** The conductivity of protein nanowires and nickel coated protein nanowires were measured. The nanowires were laid on an interdigitated electrode structure (IDE) across two electrode leads by casting a droplet of aqueous solution of protein samples.). Three protein nanowires were measured of their conductivity: protein itself, protein coated with Ni for 2 minutes (thinner Ni coating, blue curve) and protein coated with Ni for 8 minutes (thicker Ni coating, magenta curve). The conductivity of pure protein nanowires across the IDE electrodes cannot be measured.

### 3.5 Conductivity measurement of the protein nanowires

The nanowires were laid on an interdigitated electrode structure (IDE) across two electrode leads by casting a droplet of aqueous solution of protein samples (23). Three protein nanowires were measured for their conductivity: protein itself, protein coated with Ni for 2 minutes (thinner Ni coating) and protein coated with Ni for 8 minutes (thicker Ni coating). The conductivity of pure protein nanowires across the IDE electrodes cannot be measured. There was no detectable current (instrument current limit is 10 fA) passing through when the voltage swept from 3V to -3V. The current can be detected at the level of $10^{-8}$ to $10^{-7}$A (see the blue curve in Figure 7) by sweeping the voltage from 0.5V to -0.5V for the protein nanowires that was coated with Ni for 2 minutes. The current was measured at higher level of 10-7A (see the magenta curve in Figure 7) by seeping the voltage from 0.5V to -0.5V for the protein nanowires that coated with Ni for 8 minutes. These results show that pure protein nanowires are strong insulating material. When the Ni metal coated the outside of the protein nanowires, it introduced the conductivity to the protein. The thicker the Ni, the higher the conductivity was obtained as it can be seen in figure 7. However, I-V curves are not linear through origin, which indicates that the protein-Ni materials do not behave as metallic conducting. Further conducting mechanism will be investigated by electrical measurement as well as spectroscopic measurement.

### 3.6 A novel technique to make arrays of metal nanoparticles

We previously demonstrated that self-assembling native and genetically modified chaperonins that form 2D crystals could be used to organize gold nanoparticles, transition metals Pd, Ni, and Co nanoparticles, and semiconductor quantum dots into ordered arrays (19). Agarose has been used in protein crystallizations to reduce nucleation and sedimentation and grow larger protein crystals (33, 34). We discovered that the dwarf chaperonins were able to self-assemble into 2D arrays in an

agarose matix. We optimized the concentration of agarose so that its melting temperature was below 75°C, which allowed us to take advantage of the thermal stability of the chaperonins. We discovered that uranyl acetate (UA) does not stain agarose and we used UA to visualize dwarf rings, filaments, and 2D arrays by TEM in agarose gel slices.

Using Pd-activated dwarf 2D crystals in solid agarose, metallization with $NiSO_4$ and DMAB, resulted in extensive 2D arrays with Ni metal particles deposited in the centers of rings (Figure 8). By first forming Pd-activated dwarf filaments and solidifying them in agarose the nickel particles are not only coated on the filaments, but also formed nanowires with more uniform diameters (Figure 8b).

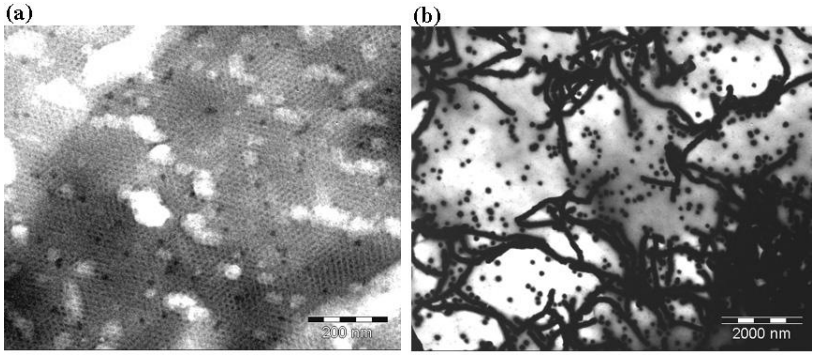


**Figure 8:** TEM micrographs showing (a) the nickel particles deposit on 2D arrays assembled by Pd activated the dwarf proteins in agarose gel, and (b) the nickel particles are coated on the Pd activated dwarf filaments uniformly in agarose gel.

## 4. CONCLUSIONS

We have demonstrated by example how a protein can be manipulated genetically to self-assemble into interesting nanostructures and how these structures can function as templates, which can be transformed by a simple chemical process (electroless deposition) from an organic to a metallic material. While our results remain crude by most manufacturing standards, we hope that our readers can see their trajectory and implications. It should be clear from our example that the intrinsic properties of biomolecules, molecular recognition and self-assembly combined with mutation, selection, and replication, have a vast potential in bottom-up manufacturing and that biomolecules will play an unequivocal role in the on-going nano-revolution.

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# Research in Micro- Nano- technology and systems: a European perspective. Opportunities in Framework Programme 7: 2007-2013

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## ABSTRACT

The Research European Programmes have paid attention to the area of microsystems since the early 90's when the Research was focused on Micro-Electro-Mechanical Systems. Since then the interest has grown into an area of Microsystems and Micro Nano Technology for a wide set of applications in which the multidiscipline and the convergence of technologies play an important role. Systems combining sensing, processing and actuating are increasingly complex involving different disciplines and integrating different technologies, and making the field of Microsystems technology expands to the field of 'Smart Integrated Systems'. Today the attention is focused in the increasing complexity and miniaturization of the systems, networking capabilities and autonomy. The recently launched 7th Framework Programme and the coordination of national or regional research initiatives will help to realise the research agenda for this strategic field for Europe. This paper will give some results of ongoing initiatives, some visions and an outlook for the future with focus in micro and nanosytems.

**Keywords:** Microsystems, Smart Systems, European Framework Programme

## 1. INTRODUCTION

The European Union (EU) has recognized the importance of the Research and Technological Development (RTD) for a country's economic growth since the earliest European Treaties in the 50's. Indeed, the competitiveness of companies and the employment they can provide depend, to a great extent, on RTD activities, especially those combining research resources in certain key areas and priority technologies. An important part of the research investments in Europe goes to the Information and Communication Technologies (ICT) area which accounts for about 40% of Europe's productivity[1] growth. In June 2005, the EC adopted the i2010 initiative[2] in which one of the policy priorities is an 80% increase in EU-wide investment in research on Information and Communication Technologies by 2010. This is necessary because Europe's investment in ICT is still behind that of Japan and the US. Europe invests only 80€ per head compared to 350€ in the US and 400€ in Japan[3]. The situation for Europe could become even worse if the R&D growth rates of India and China or the rest of South East Asia countries are maintained, reflecting the importance these countries attach to ICT technologies. There is a need to focus the research efforts on areas where Europe has recognized strengths and on new areas with high potential which must be identified with the active involvement of industry. Smart Systems Integration is one of the most important drivers of ICT, and it is also one of those promising areas where European countries have today a good competitive position, as European industry is a world leader in microsystems and related advanced technologies.

The main Research instrument in the EU is the Research and Technological Development Framework Programme (FP), where, since 1984, EU-level research and demonstration activities are funded. It was during the 4th Framework Programme (FP4) (1994-1998) when the European Commission started to pay attention to the area of MST with focus on Micro-Electro-Mechanical Systems (MEMS). The research interest started to move from MEMS towards Micro and Nanosystems (MNS) and Micro and Nanotechnologies (MNT) with the 5th Framework Programme (FP5) (1998-2002) in which the Information Society Technologies (IST) Programme emphasized the industrial applications of MEMS and MOEMS (Micro-Opto-Electro-Mechanical Systems). During the recently concluded 6th Framework Programme (FP6) (2002-2006), the attention has kept in the industrial applications of the systems covering all steps needed to form systems out of components, systems that are able to take information from the environment through sensors, to process it

[1] The views developed in this article are that of the authors and do not reflect necessarily the position of the European Commission.

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electronically, to communicate it and to 'close the loop' by taking the appropriate action. Systems combining sensing, processing and actuating are increasingly complex involving different disciplines and integrating different technologies, and making the field of Microsystems technology expands to the field of 'Smart Integrated Systems'.

Other important European initiatives emerging during the last years of FP6 are the European Technology Platforms (ETPs). ETPs provide a framework for stakeholders, including key industrial players, SMEs, public authorities, and the research community, in order to define research and development priorities, timeframes and action plans on a number of strategically important issues with industry taking the lead role. In this way, the ETPs are focused on future markets for key technologies and help Europe to keep its leadership in relevant areas. So far, 31 ETPs have been launched covering a wide range of technological challenges.[4] In the ICT area there are currently 9 related ETPs active in areas such as Satellite communications, Robotics, Photonics, or just to mention the three ETPs more related to MST, Nanoelectronics, Embedded Systems and Smart Systems Integration.

In January 2007, the 7th Framework Programme (FP7) was launched for the duration of seven years, from 2007 to 2013. The European Commission (EC) budget for these seven years is €50.5 billion, which represents a 41% increase from FP6 at 2004 prices and 63% at current prices. Similarly to previous FPs, FP7 supports research in selected priority areas aiming at making or keeping the EU as a world leader in those sectors. ICT continues being one of these priority themes in which the efforts will concentrate in areas with strategic importance where we expect to get the most out of our investments. The MST or smart systems integration is one of those promising areas.

After this short introduction, the article will first make a review of the activities funded under FP6 in the MST area. Then it will make a summary of the current European initiatives of the area. Finally, the main characteristics of FP7 will be presented giving some visions and an outlook for the future research on MST.

## 2. ACTIVITIES IN THE MICROSYSTEMS AREA UNDER FP6

The 6th Framework Programme has been active during the period from 2002 to 2006 supporting research in seven thematic priorities, being IST one of them. The total EC budget of FP6 was € 16.27 billion and the EC budget devoted to IST priority has been €3.625 billion for the four years of duration of the Programme. The research on microsystems was very relevant in the IST area whose actions addressed four technological priorities: A) Integrating research into technological areas of priority interest for citizens and businesses; B) Communication and computing infrastructure; C) Components and microsystems; and D) Information management and interfaces.

A total of six calls for proposals have been open in the IST priority in FP6. The microsystems objective was present, in a minor or larger extent, in all of them. As a result, 79 projects are currently being or have been funded in the area of micro and nanosystems, representing a total budget of €507 million, of which the EC contributes €301 million. All these projects have brought together researchers and industries from both end users and suppliers from about 500 different organizations coming from all member states, associated countries and other countries outside the EU.

The group of projects have successfully covered a complementary set of activities, ranging from technologies and systems development (e.g. MEMS, RF microsystems, plastic and organic micro-nanosystems), to product innovation and new manufacturing processes. The use of microsystems to support applications, such as health and biomedicine, food chain management, displays and robotics have also been largely covered by the portfolio of projects. Taking into account the activities of the project, we have classified the projects in six different groups:

1. Micro nano bio convergence systems
2. Sensor based systems and storage
3. Organic and large area electronics and display systems
4. Micro and nanosystems for Ambient Intelligence (AmI)
5. Manufacturing and process integration
6. Smart fabrics and interactive textiles
7. Support and coordination actions

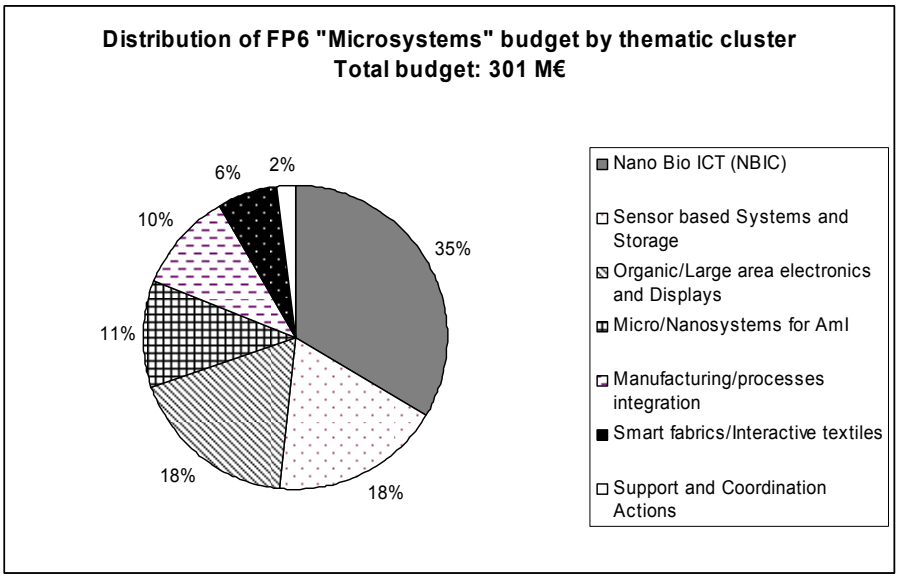


**Figure 1:** Distribution of the FP6 budget of the Micro- and Nanosystems Unit by thematic cluster.

Figure 1 shows the distribution of the FP6 EC budget between the different groups of projects mentioned above. The first group is made with projects dealing with the convergence of micro/nano, bio and information technologies. This is an emerging interdisciplinary area studying the interactions between living and artificial systems in different scales for the design of artifacts that improve or expand human cognitive and communicative capabilities, health and social well-being[5]. A total of 24 projects have been funded in this area including six large Integrated Projects (IP), and covering applications which go from health care to food quality monitoring. This group of projects has taken more than one third of the total FP6 budget of the Microsystems Unit, showing the importance and the interest of this new field. As an example, figure 2 shows the main objectives and characteristics of two of the projects included in this group. The first project is GOODFOOD, an IP that aims at developing a new generation of analytical methods based on Micro and Nanotechnologies solutions for the safety and quality assurance along the food chain in the agrofood industry. The second project showed in figure 2 is MASCOT, a Specific Targeted Research Project (STRP) aiming at creating a low-cost minimally-invasive intelligent system for the magnetic isolation and analysis of single circulating tumor cells for oncology diagnosis and therapy follow-up.

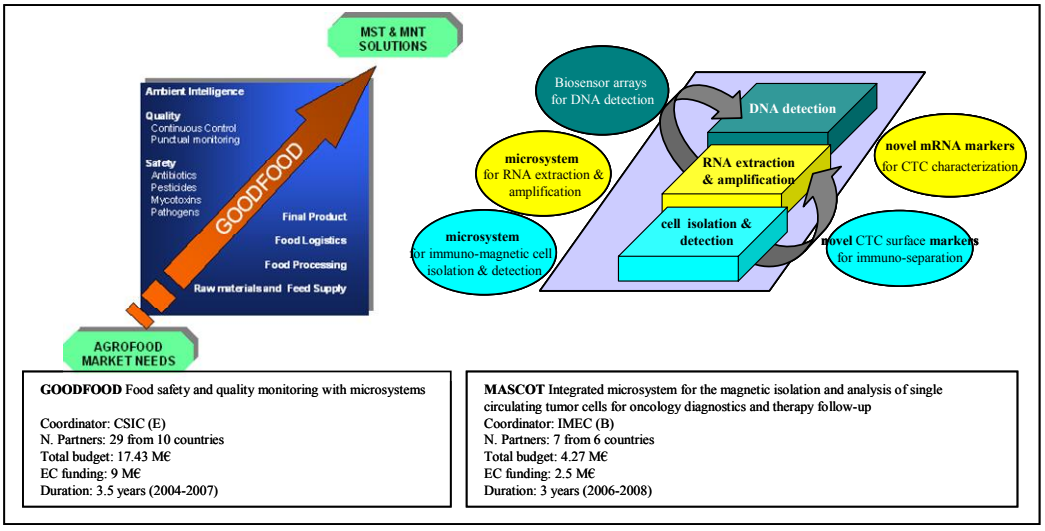


**Figure 2:** Schematic representation of two examples of projects of the Micro Nano Bio Systems group: Goodfood is an example of large IP and MASCOT is an example of a STRP.

The second biggest group in relation to budget distribution is the one dealing with sensor based systems and storage. This group includes a number of projects in which sensing is an important part of their activities, excluding biosensing. The main topics covered are MEMS based oscillators, MEMS for RF and millimeter wave communications, small 3D sensing cubes, position sensor based on magnetoresistive nano-contacts, olfaction sensors, sensors for automatic handling of nano-objects, fully autonomous helicopter, and vibration energy scavenging. Projects dealing with innovative mass storage systems are also included in this group. A total of 14 projects including 3 IPs and 2 Networks of Excellence (NoE) build up this group.

The third group deals with electronic technologies based on R&D on organic materials which can be cost effective even for large areas, and with projects over Display systems which often make use of emerging technologies related to organic materials. As an example, the objectives of some of the projects included in this group are: the applications of polymer electronics and the development of underlying technologies; research on novel materials, devices, handling and production methods for flexible displays; roll-to-roll manufacturing technology for flexible OLED devices; contact printing of electronics and opto-electronics; and smart high-integration flex technologies. Projects in the displays subgroup focus on the industrialization of emerging displays technologies related to organic materials, lightweight microdisplays, large size displays and 3D displays. A total of 11 projects, including 4 IPs build up the group.

All projects with a general view on the use of micro and nanosystems for ambient intelligence (AmI) applications have also been grouped. The emphasis is on user-friendliness, efficient and distributed services support, user empowerment, and support for human activities. Examples of topics covered by the 5 projects (including 3 IPs) which build up this group are microsystems platform for context-aware mobile services and applications; or networked multisensor system for elderly people covering health care, safety, and security in home environments.

There is also an important number of projects that deals with microsystems manufacturing technologies, from design to packaging, testing and reliability. Examples of topics including in this group, made up of 10 projects (including 3 IPs and 1 NoE) are: packaging, lithography techniques, high density integration and batch integration. A number of "service actions" projects under the umbrella of EUROPRACTICE supporting academic research, feasibility research, prototyping, training and education in the manufacturing sector are also included in the group.

The 4 projects (2 of them IPs) included in the group on smart fabrics and interactive textiles form, together with three other projects funded under another area, the cluster of EC co-financed projects SFIT[6]. Examples of topics covered are the integration of advanced fibers and materials at the fiber core, microelectronics components, user interfaces (e.g. sensors, displays, speakers), power sources and embedded software, with the objective to fulfill user needs and expectations in terms of user-friendliness/functionality, cost, fabric resistance, comfort, robustness and reliable and accurate performance.

Finally, the EC funds also projects for Specific Support Actions (SSA) or Coordination Actions (CA) in the area of microsystems. Examples of topics are: the creation of a European network pursuing the integration of new Member States and Accession Countries in the European Research Area; or to build roadmaps in various areas such as displays, RF micro-nanosystems, or applications of micro-nano-biotechnologies.

This has been a summary of the activities funded by the EC during FP6 in the microsystems area. It is important to remark that R&D on microsystems could also be present, in a minor or larger extent, in other EC funded areas such as embedded systems, nanoelectronics ("more than Moore") or e-Health, or even in another priority areas such as NMP (Nanotechnologies, Materials and Production Processes).

## 3. OTHER EUROPEAN INITIATIVES IN THE AREA

Together with the European Framework Programmes there are a number of other initiatives active in R&D of microsystems area, such as the European Research Area, under which the European Commission, Member States and the European Parliament, the scientific community and industry are committed to work together towards the creation of a non-fragmented internal market of research; the recently created Competitiveness and Innovation Programme (CIP); or the European Technology Platforms (ETPs). Due to the strategic role that the ETPs are currently playing in different

research areas, it is worthwhile mention more extensively the ideas behind the ETPs and in particular, EPoSS, the European Technology Platform on Smart Systems Integration.

The primary objective of the ETPs is to boost European industrial competitiveness. They achieve this by defining research and development priorities, timeframes and action plans on a number of strategically important issues where achieving Europe's future growth, competitiveness and sustainability objectives is dependent on major research and technological advances in the medium to long-term. ETPs focus on areas of significant economic impact and high societal relevance where there is strong public interest and scope for genuine value added through a European level response.

Under the ETPs all relevant stakeholders of strategic sector, including key industrial players, SMEs, public authorities, and the research community, come together around common objectives to define medium to long-term research and technological development with industry taking the lead role. Technology platforms play a key role in better aligning EU research priorities to industry's needs. They cover the whole economic value chain, ensuring that knowledge generated through research is transformed into technologies and processes, and ultimately into marketable products and services.

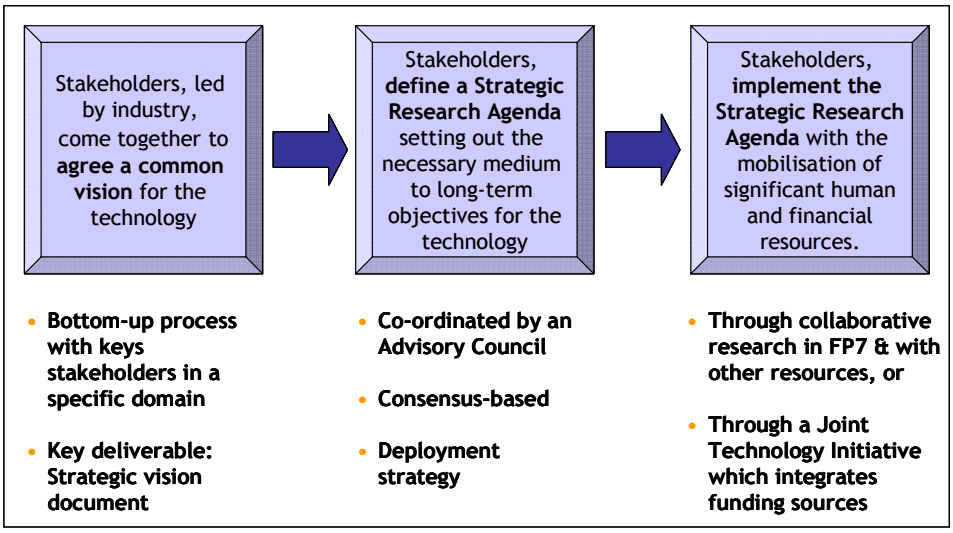


**Figure 3:** Schematic representation of the three stage approach followed by the European Technology Platforms.

ETPs generally follow a three-stage process of development which is summarized in figure 3. The first stage will bring all key stakeholders together, lead by industry, in order to develop a "Vision Document" for the development in Europe of the technologies concerned, covering a horizon of the next 10-20 years.

Upon start up, the key activities of technology platforms centre on elaborating a Strategic Research Agenda (SRA) which sets out RTD priorities for the medium to long-term, including measures for enhancing networking and clustering of the RTD capacity in Europe. This needs to take close account of the technological framework (including regulatory issues, intellectual property rights etc.) and the business environment for future market penetration. Together with the Strategic Research Agenda, a Deployment Strategy is also formulated.

The first ETPs emerged in 2002-2003. Since then, the concept has been taken up widely and there are now 31 ETPs up and running and the majority of them are now in the implementation phase of their strategic research agendas. The use of existing instruments for collaborative research already available in FP7 is expected to be the most appropriate way of providing Community support for the implementation of the majority of these research agendas. In practice therefore, Community support for this implementation would be through open calls for proposals for collaborative research (for example, integrated projects or other collaborative research instruments), research infrastructures etc. The participation of the Community in national research programmes, as provided for by Article 169[7] of the Treaty, could also be envisaged.

Nevertheless, a limited number of research agendas can be expected to be of such an ambitious scale that they will require the mobilisation of very high public and private investments, as well as a large critical mass of researchers throughout Europe and even beyond. In view of establishing and co-ordinating the necessary public-private partnerships to implement such research agendas, a mechanism called Joint Technology Initiative (JTI) has been introduced. The JTIs are based on Treaty Article 171[8], and are proposed as an effective means of meeting the needs of this small number of ETPs.

Taking into account the stage of development of the Strategic Research Agendas of ETPs, six areas have been currently identified where a JTI could have particular relevance: hydrogen and fuel cells, aeronautics and air transport, innovative medicines, nano-electronics (ENIAC), embedded computing systems (ARTEMIS) and global monitoring for environment and security.

In the area of Smart Systems Integration, the ETP EPoSS was launched in July 2006 by a group of industrial stakeholders (see figure 4) who are convinced that progress in research and development of smart systems and their integration techniques is crucial for European competitiveness.

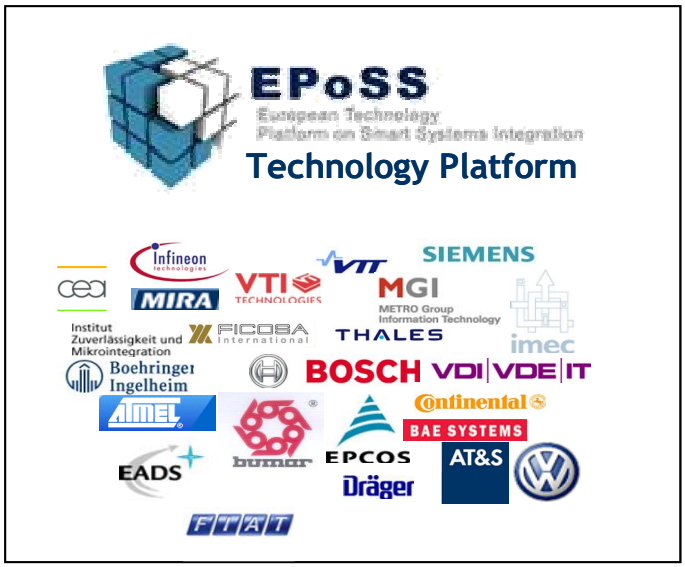


**Figure 4:** Main industrial stakeholders participating in the European Technology Platform on Smart Systems Integration, EPoSS.

Currently, European industry is the world leader in microsystems and related technologies; however there is a strong international competition which demands for a rapid product change, higher quality, lower cost and shorter time to markets. The future of microsystems will consist of integrated smart systems which are able to sense, and diagnose a situation and to decide the appropriate action. In order to keep the lead position of Europe in this area, there are a number of challenges to overcome and EPoSS will play a key role in ensuring an adequate focus of research funding in this industrially relevant area.
The main objective of EPoSS is to provide a common European approach on innovative Smart Systems Integration from research to production. In order to do so, EPoSS has already formulated a common agreed roadmap and it is currently working in defining its implementation plan. The research priorities of EPoSS have been defined in its SRA and they represent the core fields of interest of the founding members of the ETP. In particular, these priorities are:

- Development of next-generation smart systems
- Micro/nano/biotechnologies convergence
- Integration and use of smart materials
- Transfer from smart systems to viable products
- Communication and data management for smart systems
- Energy management for smart systems

- Societal impact and educational issues

Figure 5 shows an overview of the activities of EPoSS in the seven priority areas where smart systems applications are highly relevant:

1. Automotive
2. Aeronautics
3. Technologies for Information and Communication
4. Medical Technologies
5. Logistics/RFID
6. Communalities: Common technologies issues
7. Security

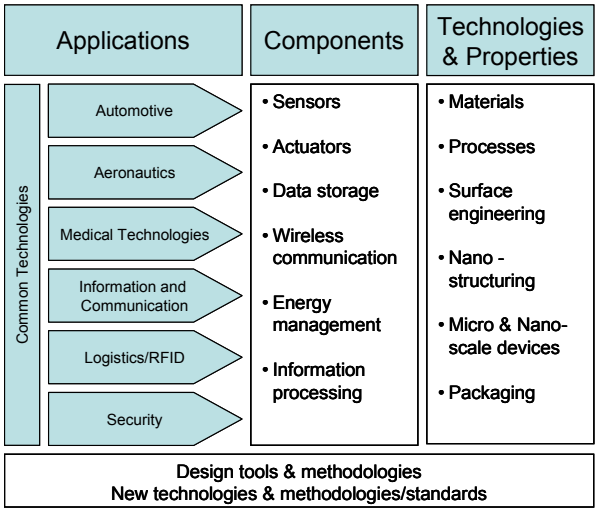


**Figure 5:** Overview of activities of EPoSS in the selected applications.

There are two others ETPs working in the Micro Nano Technologies area which complement EPoSS activities: ENIAC, the ETP on Nanoelectronics, and ARTEMIS, the ETP on embedded systems. ARTEMIS, the embedded systems platform contributes to systems integration by focusing on "systems design, distributed architectures, computing platforms, security, middleware and tools". EPoSS is essentially driven by functions. The technological solutions promoted by EPoSS are systems solutions and therefore will deliver decisive features of the end product. ENIAC, the nanoelectronics platform, is a component-level-oriented platform, focused on semiconductor development and aiming at achieving the smallest possible dimension and thus on increase of performance. This is a good basis for cooperation since these issues are not part of EPoSS activities. The "More than Moore" working group of ENIAC focuses on the implementation of the interactivity of the Silicon chips, and only the combination of nanoelectronics with other nanotechnologies such as nano-bio-technologies and nanomechanics will allow these intelligent interactive systems to be made small enough, cheap enough and sufficiently low power consuming to be used as everyday consumer products. The System-in-a-Package approach of EPoSS integrating various materials other than silicon, makes EPoSS and ENIAC really complementary ETPs, however, a strong collaboration between them is envisaged.

Currently, all existing ETPs are in their implementation phase. ENIAC and ARTEMIS will be implemented through JTIs which are expected to be launched during the second half of 2007, after the approval of the European Council. EPoSS is also facing its implementation stage, which will most probably be through FP7 collaborative projects, although other mechanisms are also being discussed.

## 4. OPPORTUNITIES OF THE MICROSYSTEMS AREA IN FP7

The current 7th Framework Programme for Research and Technological Development was launched last January 2007 for the duration of seven years (2007-2013), and, as it was the case of FP6, its main objective is to further construct the European Research Area. FP7 presents several important novelties with respect to previous FPs. The duration of the Programme has been increased from five to seven years and the annual budget has also been increased significantly (see the evolution of the annual budgets of the different FPs from 1984 to 2013 in figure 6). The total FP7 budget represents a 41% increase from FP6 at 2004 prices.

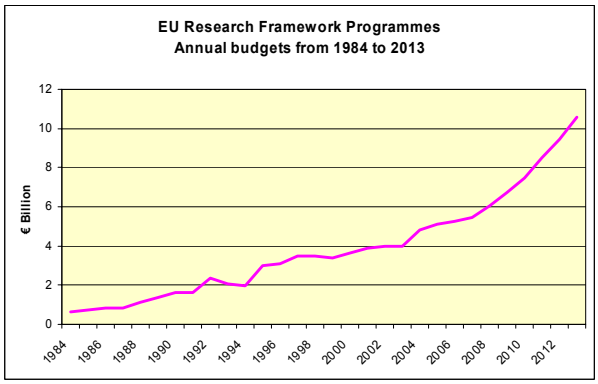


**Figure 6:** Evolution of the annual budget of the EU research Framework Programmes from 1984 to 2013.

FP7 is organized around four Specific Programmes: **Cooperation**, aiming at improving links between research and industry and to stimulate transnational cooperation; **Ideas**, managed by the European Research Council, will support the most ambitious and innovative research projects aiming at discovering new fundamental knowledge; **People**, which objective is to encourage training and mobility so that European researchers can realize their full potential; and **Capacities**, dealing with research infrastructures. Figure 7 shows how the FP7 budget is distributed between the Specific Programmes.

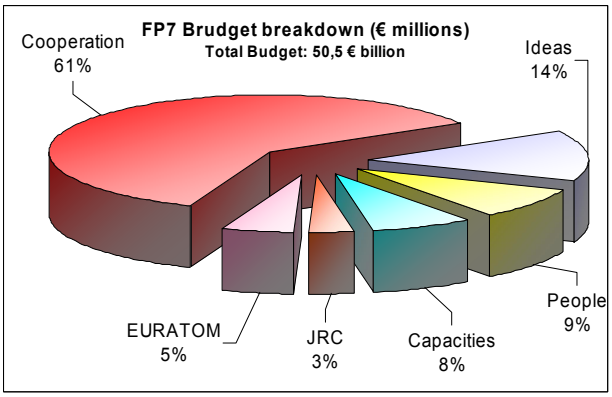


**Figure 7:** FP7 Budget breakdown between the different Specific Programmes together with the budget of EURATOM FP and Joint Research Center (JRC).

The Cooperation programme is sub-divided into ten distinct themes which reflect the most important fields of knowledge and technology where research excellence is particularly important to gain and consolidate Europe's leadership in key research areas. Their continued relevance will be guaranteed by relying on a number of sources from the research sector, including the European Technology Platforms. Important themes identified in the Strategic Research Agendas developed by the ETPs are therefore covered by the Cooperation programme. Figure 8 shows the budget breakdown of the Cooperation Programme between the ten selected themes.

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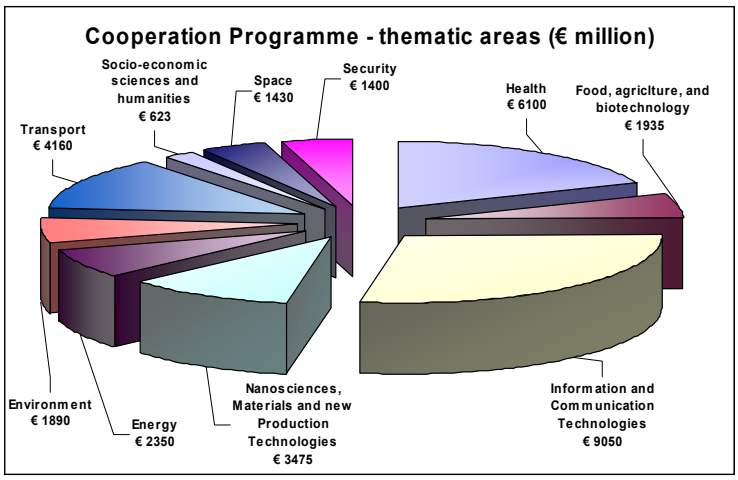


**Figure 8:** Budget breakdown between the nice selected themes of the Cooperation Programme

### 4.1. Information and Communication Technologies theme. Challenge 3 "Components, Systems and Engineering"

The work programme for the years 2007-2008 of the ICT theme of the FP7 Cooperation Programme was published in December 2006. This work programme defines the priorities for the three first calls for proposals of FP7, and it is structured around seven challenges that should be addressed if Europe is to be among the world leaders in next generation ICT and their applications. The challenges are driven either by industry and technology objectives or by socio-economic goals. Figure 9 shows a scheme of the seven ICT challenges.

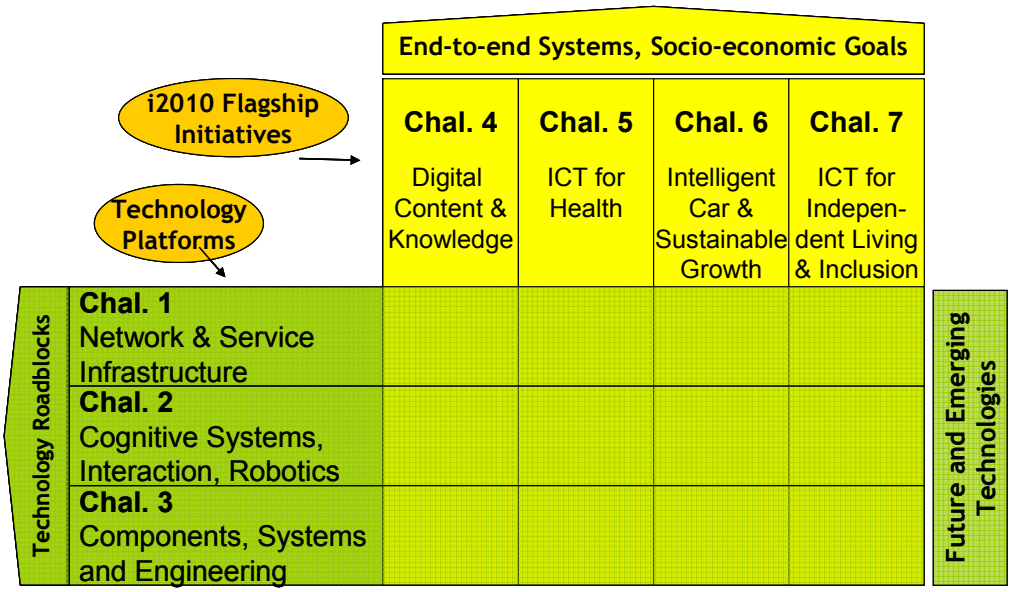


**Figure 9:** Structure of the ICT work programme for 2007-2008 around seven challenges.

Challenge 3 "Components, Systems, and Engineering" has as a main goal to strengthen Europe's position as a leading supplier of electronics components and systems. This will support the competitiveness of industrial areas such as automotive, avionics, industrial automation, consumer electronics, telecom, and medical systems. In all these domains Europe's leadership depends heavily on the capacity to engineer and produce electronic components and systems and to integrate these into products across all sectors. In pursuit of the challenge targets, a set of research objectives will be called for in 2007. These objectives have been selected through various consultations with a large group of research

stakeholders, and are in line with the Strategic Research Agendas of ETPs ENIAC (on nanoelectronics), EPoSS (on systems integration), PHOTONICS21 (on photonics) and ARTEMIS (on embedded systems). Table 1 below summarizes the seven objectives of Challenge 3 which will be called in 2007.

Table 1. Research objectives of Challenge 3 "Components, Systems, and Engineering" open in 2007-2008

| Objective number | Subject | Call |
|---|---|---|
| IST-2007-3.1 | Next generation nanoelectronics components and electronics integration | ICT - Call 1(closes May07) |
| IST-2007-3.2 | Organic and large area electronics and displays | ICT - Call 1 |
| IST-2007-3.3 | Embedded systems design | ICT - Call 1 |
| IST-2007-3.4 | Computing systems | ICT - Call 1 |
| IST-2007-3.5 | Photonic components and subsystems | ICT - Call 2 (May-Sep 07) |
| IST-2007-3.6 | Micro/Nanosystems | ICT - Call 2 |
| IST-2007-3.7 | Networked embedded and control systems | ICT - Call 2 |

Micro/Nanosystems will be one of the objectives of Challenge 3 which will be open from May to September 2007 in the FP7 ICT Call – 2. This objective will have a budget of €83 Millions, from which €75 Millions will go to Collaborative projects (IPs and STRPs) and €4 Millions to NoEs. The objective has been divided in six different areas, with no pre-allocation of budget between them. This means that the areas will compete between them with a possible result of a non- or very little funded area, if there is not enough interest from the research community or the projects presented are not of sufficient quality. The mentioned areas are the following:

a) **Next-generation smart systems**: Projects expected must provide major breakthroughs in intelligent sensor and actuator systems complexity, miniaturisation, networking, and autonomy; micro/nanoscale smart systems with higher performance at lower cost and lower power consumption for specific applications; energy-management, scavenging and storing techniques; design and packaging technologies for new sensors, actuators and microsystems, their combination and integration; innovative devices and integrated systems with very high density mass storage capacity building upon progress in solid-state semiconductors, micro/nanodevices, mechanics, optics, electronics and magnetism.
b) **Micro/nano/biotechnologies convergence**: Converging micro/nano, bio and information technologies for the development and production of integrated systems for specific applications, such as environmental monitoring, agriculture and food quality management, safety, security, biomedical and lifestyle applications. Innovative bioMEMS, biosensors, lab-on-chip microsystems and autonomous implants and bio-robots. Research may also address packaging, multilevel interfacing, manufacturing, as well as ethical and societal issues.
c) **Integration of smart materials**: Integration of micro-nano technologies and smart systems into new and traditional materials, e.g. textiles, glass, paper, etc. Major outcome is expected to be a new generation of advanced polymeric, biocompatible, bioconnective, flexible and very durable materials. Emphasis will be on integration into, for example, smart fabrics (SFIT) using micro/nanosystems at the fibre core, microelectronics components, user interfaces, power sources, software, all-in-one fabric, for personal (wearable) or other applications. Issues such as user-friendliness, quality, cost and comfort should be considered.
d) **From smart systems to viable products**: Advanced microsystems manufacturing technologies for the whole value chain (design, materials, processes, micro-/nano-scale devices, packaging testing and reliability) with a focus on cost-effective sensor/actuator and system integration technologies, supported by alternative fabrication and testing processes for short time-to-markets. Pre-industrial validation of new manufacturing concepts suitable for large-scale production will also be addressed.
e) **Smart systems for communication and data management**: Smart micro/nanosystems enabling wireless access and facilitating intelligent networking with emphasis on the hardware required for communications and the management of smart device information. This includes solutions for adaptable RF and HF technologies (e.g. RFID, RF-NEMS and HF-NEMS). Data management, storage and processing functions of smart systems will also be addressed.
f) **Support actions** will ensure broad access to micro/nanosystems manufacturing technologies, in particular by SMEs, identify training and education needs of the area proposing appropriate measures and establish specific measures aiming at coordination and dissemination of smart systems integration RTD at European level.

The expected impact of the projects funded can be summarized as follow:

- Substantial improvement on various aspects of smart systems integration: Higher product quality and reliability, increased miniaturisation, integration and functionality, lower costs, reduced power consumption, higher speed requirements and/or shorter time-to market.
- Transformation of industrial production by adding intelligence to process control and the manufacturing shop floor, and by improving logistics and distribution - thereby increasing productivity.
- Increased market share for European companies across different industrial sectors by delivering systems with new functional capabilities and improved quality within a competitive timeframe.

As a summary, the area of micro and nanotechnologies and systems will be certainly well covered in the ICT Theme of FP7. Currently, the workprogramme for the years 2007 and 2008 has been published and the area has kept its interest and importance as in the previous FP6. The different objectives and areas which will be open in the coming FP7 workprogrammes will very much depend on the results of the first two ICT calls of proposals in 2007.

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