SmartEN: A Marie Curie Research Framework for Wireless Sensor Networks in Smart Management of the Human Environment

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Abstract. Even though there is significant research work performed in the fields of wireless sensor networks, civil infrastructure reliability and management, most of the work is fragmented and there is no significant activity in performing multidisciplinary structured research for developing integrated smart and dynamic systems for effective management of the built and natural environment. The aim of SmartEN is to push innovation through the development of a research training network that will focus on the development and effective integration of emerging technologies targeting key application areas of current interest to Europe and the world.

Keywords: Wireless sensor networks, signal processing, proactive management, infrastructure reliability.

1 Introduction

There are increasing concerns regarding the environmental impact of human actions, the use of the environment and climate changes. These are coupled with ageing infrastructure systems, increasing urban population, continuously growing and changing demands on the built and natural environments as well as limited financial and depleting natural resources. The renewed EU Sustainable Development Strategy [Renewed EU Sustainable Development Strategy, Council of the European Union, 10917/06, Brussels, 26 June 2006] sets out a single, coherent strategy on how the EU will more effectively live up to its long-standing commitment to meet the challenges of sustainable development. It recognizes the need to gradually change our current unsustainable consumption and production patterns and move towards a better integrated approach to policy-making. Some of the key priority challenges are: climate change and clean energy, sustainable consumption and production, and conservation and management of natural resources. These issues pose significant challenges for designing and managing the human environment in a sustainable manner. Until now, research has been focused on the development of proactive risk-based approaches for civil infrastructure reliability and management with benefits in improved performance, safety and cost.

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However, there are significant uncertainties associated with the various predictive models directly affecting the quality of the decision making mainly due to the limited amount of information available on the changing condition, demands and actual performance of various systems. Recently, a new generation of miniature wireless sensor platforms which utilize novel Digital Signal Processing, microprocessor and communication technologies has emerged. These can be adopted to obtain large quantities of highly diverse sensor data that are continuously collected over a long period of time from multiple targeted locations within a system, therefore providing significant insight on the condition, demands and performance of the system. These developments open up a completely novel area of multidisciplinary research and new research directions towards the 'smart' management of the sustainable environment. Wireless Sensor Networks (WSN) is a fast growing technology which can be widely used in a number of sectors associated with key aspects of the management of the human environment. There are significant opportunities presented in this area by the emerging technologies on wireless sensors and communications which can be exploited to develop dynamic and smart systems for strategic management. Even though there are top research institutions around the world, which are focusing their activities in the development of WSN technologies and others that are focusing on civil infrastructure reliability and management research, most of the research activity is fragmented and there is not any significant activity in performing multidisciplinary, intersectoral structured research for developing integrated smart and dynamic systems for effective management of the built and natural environment.

The aim of SmartEN is to fill this technology gap and push innovation through the development of an initial research and training network that will focus its activities on the development, effective integration and increased utilisation of emerging technologies in wireless sensors, communications and proactive management targeting key issues of current interest to the European Commission and internationally. These will include application areas in monitoring and smart proactive management of Structural Systems, Heritage and Infrastructure, Transportation Infrastructure Systems and Urban Microclimate. SmartEN will advance the state-of-the-art in the development, integration and application of sensor technology in the specific sectors of ***Wireless Sensor Networks*** (WSN), ***Sensor Signal Processing*** (SSP), ***Non Destructive Evaluation*** (NDE) and ***Smart Proactive Management*** (SPM), for the benefit of the human environment (Figure 1).

The SmartEN Initial Training Network (ITN) project, which is funded under the Marie Curie FP7 program, aims to train the next generation of researchers, engineers and research managers in the field of monitoring and smart proactive management of the built and natural environment by effectively developing and integrating novel WSN and digital signal processing (DSP) technologies in proactive management for the benefit of the human environment. The consortium, shown in Table 1, consists of fifteen partners with world-class competence and is inherently interdisciplinary as it combines expertise from areas like infrastructure reliability and management, digital signal processing, communications, computer engineering, materials, non destructive evaluation, information technology and wireless communications. The network consists of partners with established experience in civil and electrical engineering related disciplines from academia, research centres, and the industry. In addition to the European partners the consortium also includes nine Visiting Scientists who are

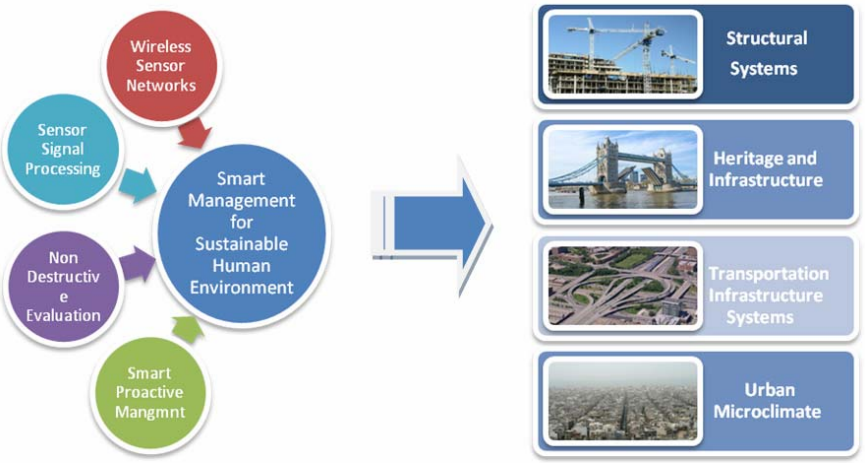

Fig. 1. Research Training and Application Areas of SmartEN

Table 1. SmartEN Participants

1	Cyprus University of Technology (CUT), Cyprus
2	Research Academic Computer Technology Institute (RACTI), Greece
3	Imperial College London (IC), UK
4	Research and Education Laboratory in Information Technologies (AIT), Greece
5	University of Surrey (UNIS), UK
6	University of Pavia (UPV), Italy
7	Federal Institute for Materials Research and Testing (BAM), Germany
8	Swiss Federal Laboratories for Materials Testing and Research for Industry (EMPA), Switzerland
9	Ecole Nationale Supérieure des Télécommunications (ENST), FR
10	Comsis, (Comsis), France
11	Design for Life Systems, UK
12	COWI (COWI), Denmark
13	Network Rail (NR), UK
14	Parsons Brinckerhoff (PB)UK
15	Intracom (ICOM), Greece

leading experts in the key disciplines represented in the project from top universities and other institutions worldwide.

2 Overview of Previous Work

The design and management of the built and natural environment has moved towards a more proactive risk based approach considering the whole life cycle of a system [1].

This encompasses the use of life cycle design and assessment and multi-objective optimisation [2,3] and the adoption and optimisation of proactive measures such as preventative maintenance [4,5]. Other important elements within this framework are component and system probabilistic assessment methods [6] and probabilistic long term performance and deterioration modelling [7]. These have been augmented with information from global dynamic monitoring through the use of system and damage identification methods [8,9] and the use of inspection and monitoring information integrated through Bayesian updating methods [10,11]. Recent trends in structural health monitoring are towards the application of statistical signal processing techniques to diagnose damage which offer improved accuracy in damage localisation and detection [12]. The combined developments in this whole area provide a tremendous potential for more rational and effective proactive management. However, there are still many research challenges that need to be addressed to integrate effectively all these elements within a proactive framework and achieve their full potential.

Such developments are interlinked with the effective integration with emerging technologies in wireless sensor networks (WSN) and communications which open up tremendous opportunities for information gathering on a continuous basis that can reduce uncertainty in the modeling and decision making and result in effective life cycle strategies. Recent developments in this area include many solutions for software and hardware design, communications, distributed signal processing, data mining and fusion, node and source localization methods, and middleware design. The former include application-tailored hardware and software solutions that have been evaluated with short term deployments [13-16], off-the-shelf hardware components [17], and modular software and hardware designs [18-19]. Communication problems are tackled using distributed solutions like cooperative relaying networks [20], virtual MIMO systems [21], cooperative beamforming systems [22], and smart antenna systems [23]. Data mining and distributed data fusion methods are inevitable for reducing the massive amounts of raw data produced by WSN monitoring the physical world [24], and the emphasis has moved towards the use of WSN with distributed learning and processing capabilities [25]. Localization and synchronization of sensor nodes is critical for most of the previous distributed algorithms to work. Algorithms utilize either Time Difference Of Arrival (TDOA) [26], Round-trip Time Of Flight (RTOF) [27], Direction Of Arrival (DOA) [28], or Received Signal Strength (RSS) methods [29], with the former being the most accurate, and the latter mostly suited for the limited hardware of sensor nodes. All the aforementioned approaches have to be effectively handled by an intelligent Middleware that will be easy-to-use by inexperienced users, and provide transparent internet connectivity. The existing approaches for WSN middleware design include virtual machine-oriented [30-32], database-inspired [33-35], mobile-agents based [36-37], or application driven [38] designs.

There is a large community of researchers working in all the above areas and a number of centres around the world focusing in a specific area (such as the 'Cambridge MIT Centre on Smart Infrastructure', The 'Centre for Advanced Monitoring and Damage Detection' at University of California Irvine, the 'John A. Blume Earthquake Engineering Centre' at Stanford, the 'Advancement of smart infrastructure sensor technology' at the University of Illinois, 'Intelligent Infrastructure Institute', Drexel University and the 'Information Technology Research ITR Collaborative Project on Health Monitoring of Highway Bridges and Infrastructure' in California).

In some areas like structural health monitoring guidelines covering the basic aspects of such applications have been developed (SAMCO, ISIS, FIB, ISO, FHWA). There are also a number of national, European and international networks like SIMONET (UK), SAMCO (EU) and ISHMII (International) who have contributed significantly in bringing together various stakeholders in an attempt to promote dialogue and understanding of needs and emerging capabilities. However, these networking platforms are heavily weighted towards the infrastructure community with limited participation from the WSN and communications community. Furthermore, these networks offer limited opportunities for advanced training of the next generation of research leaders and decision makers in this area.

There are significant technological developments in the various components that can contribute to the smart management for sustainable human environment. The new technical challenges lie in the improved exploitation of these technologies through integrated multi-disciplinary life cycle management approaches with the development of effective interfaces between the various key disciplines. The importance of integrated management environment and life cycle approach are recognised by the European Commission COM(2005) 718 [39] and the Sixth Environmental Action Programme [40] which is calling for the preparation of a 'thematic strategy for sustainable use of management of resources'. Furthermore, G8 ministers responsible for science and technology argue that in the long term making existing technologies more efficient will not be enough to solve a problem, instead 'fundamental breakthroughs in science and technology will be essential' (summit June 15 2008). The most significant barrier in achieving significant breakthroughs in these areas are the lack of: 1) a community of high calibre researchers who have a broader understanding of the whole spectrum of technologies required to achieve truly integrated multi-disciplinary solutions and who are trained to work in multi-disciplinary research environments and 2) a world class research environment encompassing the whole range of specialisations providing a powerful scientific base for training and technological developments in this area. The SmartEN ITN aims to fill this gap and place Europe in a unique position worldwide by providing a unique world class training and multi-disciplinary scientific research base moving Europe to the forefront of research in this field. Furthermore, the SmartEN ITN holds the potential for achieving significant breakthroughs with tremendous benefits for a sustainable human environment.

3 SmartEN Objectives and Challenges

The main objective of the SmartEN project is to implement a joint multidisciplinary research training programme which will be focused on the growth of scientific, technological knowledge and professional skills through research on individual, personalised projects in the field of smart management for sustainable human environment. The network aims to achieve the following objectives:

- *Research:* To conduct top level research and training and devise innovative solutions in the areas of monitoring and smart proactive management of Structural Systems, Heritage and Infrastructure, Transportation Infrastructure Systems and Urban Microclimate arising from changing and growing demands in the built and natural environment and deteriorating climate changes.

- *Education:* To educate the next generation of intersectional and transnational researchers in the area of smart management of the sustainable environment and provide them with a unique range of skills and a network that will open up challenging and attractive career perspectives.
- *Convergence:* To take forward the state-of-the-art in wireless sensor communications, digital signal processing and non destructive evaluation for the successful application of wireless sensors in the smart proactive management of the built and natural environment, by providing an impetus for infrastructure management and wireless sensor research groups to integrate and intensify their research effort in important innovative areas

SmartEN will target applications of Structural Systems, Heritage and Infrastructure, Transportation Infrastructure Systems and Urban Microclimate. Namely, it aims to direct its research activities towards the following fields:

1. To develop new wireless communication protocols and localisation algorithms that will lead to a new generation of wireless sensors tailored to the needs of a sustainable human environment management which will enable engineers to assess constructions' condition and detect defects in a more accurate, much faster and less costly way.
2. To extend the energy harvesting technologies and investigate renewable energy sources to power wireless sensor networks for applications in remote, completely isolated utilities and transportation infrastructures.
3. To enable automated, cost-effective application of NDE in remote and hazardous environments and reduce the error levels introduced by manual operation, infrequent data collection and interpretation of data.
4. To develop innovative proactive management methodologies for aging depleting infrastructures through better monitoring of the health of their assets thus enabling stakeholders to provide better services to the citizens including reduced disruption, improved safety, lower costs and reduced environmental impact.
5. To enable continuous monitoring of heritage and infrastructure systems of great cultural importance through the development of models for the evaluation of the performance and health of a structural systems and the detection of damage.
6. To facilitate the collection, transmission, processing, modelling and interpretation of huge quantities of highly diverse environmental sensor data for urban microclimate monitoring.
7. To develop technologies that will enable the development of optimum new designs for effective smart life cycle management of civil infrastructure through the implementation and integration of wireless sensor networks and NDE.
8. To contribute to the process of developing and improving standards in various aspects related to smart management for sustainable human environment. Such standards are the ones being produced by CEN/TC 350 on environmental performance and life cycle cost performance and service life planning.
9. To realise the research results to innovative prototype commercial systems and products and prove their performance in real world conditions. The network greatly supports the training of the researchers in the whole cycle of product research and development (R&D), from research to prototype implementation, integration testing and commercialisation. SmartEN results are expected to produce products that

will solve important infrastructure monitoring and management problems and enhance the life of the European citizen.

Furthermore, the project aims to change the face of this research field and raise it to another level where inter-disciplinary research has a significant role to play. The proposed work and interactions between partners will provide the challenges and opportunities for developing technologies and methodologies that will enable moving away from reactive and fragmented to proactive and integrated approaches which hold the potential for achieving performance, safety, cost and environmental benefits on a much greater scale.

SmartEN aims to span its research in all the technological challenges affiliated with deploying WSN for NDE and smart proactive management, starting from the device level to the application. Namely, SmartEN will focus its research on the main challenges concerning:

1. the density of nodes necessary to capture relevant information with minimal energy expenditure
2. the design of interaction mechanisms among the nodes that limit the possibility of congestion when relevant events occur
3. the optimal hardware design to maximize the network lifetime
4. the tolerance to node failures and the vulnerability to natural or intentional attacks
5. the distributed transmission and coding schemes that provide the optimum trade-off between hardware complexity and energy efficiency
6. the localization and synchronization algorithms that provide adequate accuracy without depleting network resources
7. the middleware design which will enable robust over-the-internet access, transparency and reconfigurability
8. optimum sensors arrangement to achieve targeted system monitoring
9. design of dynamic and flexible monitoring and inspection regimes
10. improved assessment and long term performance modelling targeting system performance, spatial variability and effective treatment of uncertainties
11. continuous information systems in order to improve decision making and management strategies
12. new methods for incorporating information from diverse sources of different type, spatial and temporal coverage, quality and reliability
13. combined use of quantitative and qualitative information in model updating and decision making
14. combined use of damage identification with monitoring and NDT inspection for improved damage detection and sizing capability
15. integrated modelling of various proactive interventions
16. life cycle assessment and design incorporating multi-dimensional and multi-source information systems
17. dynamic multi-objective strategy optimisation for smart life cycle strategy optimisation.

4 Work Programme and Methodology

SmartEN has managed to bring together a collaborative research network that will focus its activities on research and training in the disciplines of WSN, SSP, NDE and SPM. Each of the above areas defines an individual work programme which requires a high level of interdisciplinary collaboration. It is considered that the specific work-programmes and work-programme research themes illustrated in Figure 2, and the interaction between them provide a very significant impetus for transfer of knowledge (ToK) within the proposed research network. End-users will identify the requirements for new technology and will carry out practical evaluation of the developed methods and devices. Under the umbrella of the four application areas, shown in Figure 2, multidisciplinary projects will be developed which will involve research themes from more than one work-program. Six to seven SmartEN partners will collaborate in each individual project with a view of reinforcing links between them and achieving better integration between the various disciplines. Partners were selected to carry out work on each individual project according to their expertise in the related research area, their research infrastructure and their training facilities in associated topics, with the choices being "quality controlled" by internal and external experts. Academic and industrial research groups will work together to meet the interdisciplinary needs associated with the design, development and testing of the new techniques and devices.

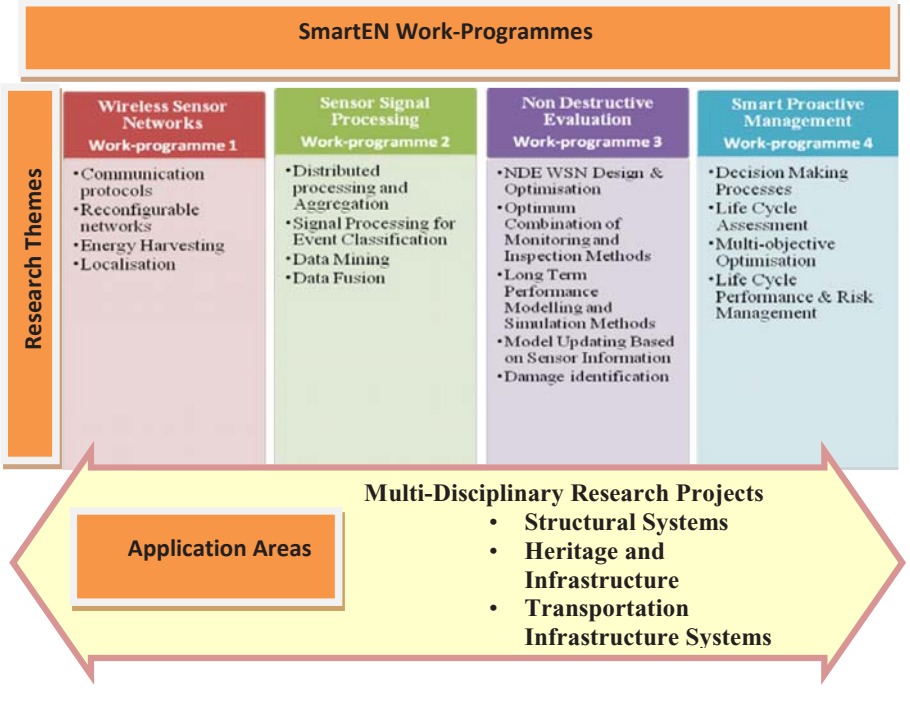

Fig. 2. SmartEN Work Programmes, Research Themes and Application

The following paragraphs identify the key scientific challenges in this area which are associated with the various component technological fields as well as the challenges and opportunities presented in attempting to integrate these fields to develop complete systems for smart management for sustainable human environment. These are outlined below within the context of the scientific programme of the project. Current research ideas and techniques are highlighted together with the future research that needs to be undertaken in order to move away from the current fragmented approaches developing in each discipline and specialisation in order to move towards integrated total solutions and systems.

4.1 Work Programme 1 – Wireless Sensor Networks

This work program (WP) will focus on training researchers in the critical area of wireless sensor node and network design, implementation and deployment. Intersectoral research will be deployed in the beginning of the project in order to gain a better understanding of the challenges involved with the NDE and smart proactive management applications, and lead to an effective design and evaluation of wireless sensor nodes, the basic building blocks of the system. Inter-disciplinary research and transfer of knowledge is also expected between work programs 1 and 2, so that signal processing and node design are coordinated.

Research Theme 1: Communication protocols
The goal of this research theme (RT) is to provide new knowledge in the field of communication protocols for wireless sensor networks, in areas such as multi-hop communications, cooperative relaying networks, energy efficient MAC and routing layer design, secure and trusted communications, virtual MIMO systems, interference mitigation, cooperative transmission and beamforming systems, smart antenna systems for sensor networks, cross-layer optimization algorithms. The scientific approach to this RT is to investigate and focus on the tradeoffs between algorithmic complexity and overall system performance and sustainability. We therefore envision that a successful completion of this RT will not only produce new protocols and standards for WSN, but also provide new approaches to the design of WSN.

Research Theme 2: Distributed OS for Reconfigurable Sensor Networks
Due to the restricted resources of WSN, each node can be programmed to perform a limited number of tasks. This could lead to wireless sensor networks where individual nodes perform a subset of the overall required sensing and processing tasks. In this RT focus is on the development of a distributed operating system (OS) that will be able to support network reconfigurability, following the changing requirements of the application. The goal is that the OS will not rely on individual node addresses to perform the changes but will rather monitor the changing needs and spatial distribution of events within the network structure.

Research Theme 3: Energy Harvesting and Conservation
One of the most critical points in meeting the goals of the project is to ensure that nodes will be able to operate unattended for large periods of time, without being connected to a power-line network, in order to take advantage of the low-cost deployment

and sustainability of such a choice. The objective of this RT is to build sensor node hardware that will meet a set of specialized requirements related to both digital hardware characteristics and node lifetime. Several technologies will be examined for increasing the autonomous nature of sensor nodes, through energy harvesting solutions. At the same time, all the different building blocks of the node hardware (sensing, processing, communication, localization, synchronization, battery and energy harvesting circuitry), will be investigated and specialized to the needs of the NDE and smart proactive management applications, while being optimized for low energy consumption.

Research Theme 4: Localization
This RT deals with one of the most difficult problems in wireless sensor network technology. Localization is a network function that requires the synergy of both hardware and software mechanisms, and is applied both for finding the relative and absolute locations of sensor nodes, as well as for localizing and tracking events in the network environment (i.e, crack detection in large structures, land movements in landslide prediction etc.). The requirements of different localization algorithms focusing on different application scenarios could be quite diverse, ranging from fractions of a millimetre to a couple of meters. A successful outcome of this RT would be to produce new algorithms and localization systems.

4.2 Work Programme 2 – Sensor Signal Processing

The focus of this WP is on the critical area of signal processing and energy efficient wake-up strategies for event based monitoring with wireless sensor networks. Signal processing in such resource constrained nodes is not trivial, therefore interdisciplinary research is expected to be triggered with the beginning of the project between WPs 1 and 2 to investigate the limitations and capabilities of signal processing algorithms within the desired system architecture. Naturally, this WP will collaborate with WP 3 and 4 in inter-sectoral research activities that will set the system requirements for the algorithms' specifications.

Research Theme 1: Distributed processing and Aggregation
Due to the redundancy of information, the limited resources of sensor nodes and the requirements of the application, distributed algorithms are often needed in WSN to achieve the goals of the application. Distributed signal processing algorithms like distributed compression, aggregation and distributed coding schemes could provide a means of reducing communication overhead, and energy dissipation. A successful outcome of this RT would be to develop a framework and specific algorithms for cluster or network wide data analysis and inter-nodal negotiation which allows for a reliable autonomous evaluation of potential alarm situations. The wireless sensor network should be able to autonomously and adaptively switch between different alarm states based on the intensity of the critical parameters across the network, and to adapt the data acquisition, analysis, communication, and evaluation policy according to the specific alarm state. The event based wireless sensor network will be evaluated with a long term field test focusing on vibration monitoring of a construction site.

Research Theme 2: Signal Processing for Event Classification
In this RT as the goal is to use signal processing on sensor individual nodes to take advantage of the proximity of sensors to the monitored events, taking into account the limited resources of sensor node hardware. Algorithms that will be investigated will be defined through an inter-sectoral research phase, where the type of algorithms, their accuracy, latency, complexity, power needs will be discussed. The work will include design of signal processing algorithms for ultra low power acceleration sensors for individual event detection, and for energy efficient signal conditioning boards with resistance strain gauges. The event based wireless sensor network will be evaluated with a long term field test focusing on fatigue monitoring of a railway bridge. The research would lead to new knowledge in the fields of signal processing for resource limited devices, or even to new approaches for the hardware design of sensor nodes.

Research Theme 3: Middleware
This RT will focus on the field of energy and communication efficient data mining to detect and classify events, and on fusion techniques, which will combine data from multiple sensor sources and gather information in order to achieve inferences. Fusion in low, intermediate and high level, depending on the processing stage at which fusion takes place will be examined. Findings in data mining and fusion will lead to an intelligent middleware design that will sit on top of the distributed OS of the WSN, enable reconfigurability options, be transparent to the inexperienced users of NDE and smart infrastructure management applications, and enable distant site monitoring through easy-to-use internet interfaces.

4.3 Work Programme 3 – Non Destructive Evaluation

This WP will focus on the area of non destructive evaluation. Strong interaction between the five sub programmes in this package is required as well as the other WPs to achieve integration between these specialisations within a smart proactive management framework. Interaction with industry is also pivotal to the success of this programme in order to focus training and research towards the needs of end users.

Research Theme 1: Optimum Sensor Locations and Requirements for NDE
The objective of this RT is to identify where and what needs to be monitored in a system and determine the requirements of the sensors in terms of type of measurement, spatial and temporal coverage and reliability. The goal is to move towards optimum sensor arrangements and specifications to achieve targeted and efficient monitoring, avoiding mass collection of unused information. There are key competing objectives here which are maximising the amount and quality of information and minimising the processing effort and cost of the overall system. This multi-objective optimisation problem will require expertise from researchers from across the different specialisations and a high degree of intersectoral research is envisaged within this RT enabling multi-disciplinary research collaborations. The success of this RT would be a crucial part of the whole programme linking the main disciplines of electrical engineering and civil engineering.

Research Theme 2: Combined Monitoring and Inspection Systems
This RT will focus on the areas of inspection and Non Destructive Testing methods (NDT) and enable them to tackle the design of systems which can augment the information normally obtained from inspections only with continuous monitoring systems. The goal is to develop methods for designing combined flexible and dynamic monitoring and inspection regimes that optimise the efficiency of the information. The continuous monitoring sensor networks can provide a wider spatial and temporal coverage of the system with a relatively lower level of accuracy and cost while acting as a warning system flagging the areas/locations where more expensive and accurate NDT inspections are required. This RT will need to be combined with the decision making process to determine when NDT is required. It will bring closer the research communities across all disciplines of SmartEN providing a powerful platform for effective integration of different technologies.

Research Theme 3: Assessment and Long Term Performance Modelling
The objective of this RT is to provide assessment and long term performance modelling of systems subjected to ageing, deterioration and changing demands. Risk and reliability methods will be examined, which provide a rational framework for taking into account uncertainties in modelling and predictions affecting the quality of decision making. Challenges to be addressed in assessment and long term modelling targeting system performance include spatial variability, and effective treatment of uncertainties. A key target is reducing the uncertainty in the predictions using new knowledge from monitoring and inspections.

Research Theme 4: Performance Model Updating Based on Sensor Information
A central goal of SmartEN is the reduction of uncertainties in modelling and predictions through continuous information systems in order to improve decision making and management strategies. This will require new updating methods to be developed for incorporating information from diverse sources of different type, spatial and temporal coverage, quality and reliability which may also require the combination of both quantitative and qualitative information. This will raise the research challenge to a level of continuous multi-dimensional system updating. The aim is to enhance current practice with an improved information system and updating.

Research Theme 5: Damage identification
The objective is to conduct research in the area of damage identification methods that enable changes in the system to be detected, located and to some extent quantified with varying degrees of accuracy. While there have been significant developments in this area, these methods are only effective in identifying large changes from extreme events such as earthquakes rather than small changes due to deterioration. The goal of this RT is to explore how combined use of damage identification with sensor networks, NDT inspections and signal processing can improve the capability of detecting and quantifying damage and deterioration.

4.4 Work Programme 4 – Smart Proactive Management

This WP will focus on smart proactive management providing the overall framework for linking all WPs. It comprises a key element of Smarten which holds the potential to make a significant contribution in the area of smart proactive management of the human environment.

Research Theme 1: Proactive Management Strategies
In this RT focus will be on the philosophy, opportunities, value and techniques of proactive management within the context of life cycle management of complex systems. There is a whole range of proactive interventions that can beneficially be employed to improve management strategies including preventative, corrective, modifications, change of use, restrictions, replacements etc. The goal is to be able to model their effects within combined proactive strategies, and not in isolation, and being able to improve their modelling and reduce uncertainties through monitoring and inspection systems. Integration of these models and reduction in uncertainty provides a more rational basis for deciding what actions are needed and when to maintain the system at the required level of performance, risk, cost, environmental impact etc within the whole life cycle of the system. Probabilistic modelling and updating and multi-objective optimisation methods are important elements here.

Research Theme 2: Life Cycle Design and Assessment
In this RT the life cycle perspective will be studied. The goal is to develop life cycle strategy development methods with all the challenges and opportunities presented by the adoption of extensive sensor monitoring systems providing multi-dimensional and multi-source information that needs to be assimilated and effectively used within the life cycle management process. Such systems need to be flexible and adaptive to meet future changing needs and their design optimised to maximise the benefit from the information obtained. This opens up a bigger area for research which is the design of smart proactive management systems for sustainable management of the human environment.

Research Theme 3: Multi-objective Optimisation
An important element of the life cycle design and assessment is how to manage with competing objectives. These include performance, risk, cost, safety, environmental impact, creation of jobs etc. and require the use of multi-objective optimisation techniques. The goal is to use multi-objective optimisation within the context of proactive life cycle strategy optimisation. Recent developments in this area incorporated the effects of various proactive actions like inspection, preventative maintenance and more recently limited monitoring. The goal in this RT is to develop methods that enable planners to consider the possible effects of various proactive actions together, and not in isolation, as well as capitalise on the continuous information system provided by the sensor networks. These issues need to be addressed in a dynamic system where models will be updated continuously therefore affecting the future predictions and decision making. This presents new dimensions to the research challenges and holds the potential for maximising the benefits in terms of performance, cost, risk, environmental impact etc.

4.5 Horizontal Integration through Multi-disciplinary Research Projects

The main work programme and research themes have been outlined above. Within this scope a number of individual research projects will be defined for the nineteen Marie Curie Fellows employed on the programme. The projects will be defined to combine partners from the main disciplines of civil engineering and electrical engineering as well as academic/research organisations with industrial partners giving the opportunity to the fellows to gain experience from the various bodies involved in the development and application of such methods.

These projects aim to:

- Give the opportunity to the MC fellows to develop expertise beyond their core area through short duration placements with other partners and develop a good level of understating of related fields which are important components of the development of integrated solutions. This will be achieved through short placements at both academic/research and industrial partners as well as through the series of network wide and local training events that will be organised.
- Enable researchers to focus more on the integrating technologies moving away from isolated insular research efforts and topics. Understand how their work links into the other components that are necessary for integrated solutions which will enable them to focus their work and achieve more effective component methodologies by being aware of the needs and constraints posed by the other discipline components required in an integrated solution.
- Exploit fully the complementarity between the expertise of the various partners as well as their research and training infrastructure.
- Provide the opportunity to researchers to be exposed to experts and research in complementary fields, promote long term networking and establish effective lines of communications between the various experts, researchers and end users.

5 SmartEN Applications

In the past 100 years, the world's population living in cities has grown from 14% of a population of 1.6bn to over 50% of the 6.6bn today; and by 2030 it is forecast that 5bn people will live in urban conurbations. This statement alone emphasizes the increased demands on buildings, infrastructure, transport and the interaction and the effective monitoring and control of the urban microclimate. It clearly highlights the dependence of the planet's population on sustainable well-engineered systems, and the importance of developing technologies that will facilitate and optimize the design and management of structural systems for buildings and civil infrastructure and the effective interaction with and control of the urban microclimate.

The key areas of application to be addressed within SmartEN target the four key areas highlighted above namely; Structural Systems, Heritage and Infrastructure, Transportation Infrastructure and Urban Microclimate. A brief description of the areas of application is given below.

Structural Systems

Research within SmartEN will focus on the development of new and integrated technologies which will enable the design and maintenance of smart structures with the

aim of achieving more sustainable systems. It is envisaged that the application to new structures will provide the in built capability of sensor networks, signal processing and smart decision making for effective life cycle management. On existing structures various technologies can be developed which can be mounted with minimal intervention on the structure to provide a similar capability. Such systems should be able to monitor the structural and environmental loadings, the actual performance of the structure, changes in the structure due to long term deterioration processes, environmental effects and accidental and extreme environmental events such as earthquakes, typhoons and floods. Another dimension of the smart monitoring and proactive management capability to be explored for structures relates to thermal losses or gains and the energy efficiency for heating, cooling and electricity consumption and various environmental comfort parameters. The sensor network monitoring systems will be linked with assessment and whole life based management systems for early detection/recognition and proactive response to observed and expected changes in the structure's demands and performance. The overall aim of the application of these technologies is to move towards sustainable systems using rational approaches for optimal solutions which balance various competing objectives such as whole life cost, safety, reliability, energy efficiency and comfort.

Heritage and Infrastructure

The application issues highlighted above for structural systems are also relevant to the need for smart effective management systems for maintaining priceless heritage and ageing infrastructure systems while there are specific concerns and characteristics in these groups of structures which require a specific focus in the research programme. There are specific constraints which apply to heritage structures such as the need to maintain the original form and materials with little or no interventions, dealing with very old already weakened structures, a long and unknown history of loading and performance and possible interventions, different materials and methods of construction etc, issues that need to be addressed specifically in developing technologies for this area of application.

The application to infrastructure systems, while similar in many respects to structural systems, introduces a number of additional aspects which differentiates the way such methodologies need to be developed and applied at a network level. In the case of network application the main purpose would be to develop strategies to support financial planning, budget requests, bid prioritisation, monitoring of the performance of the network and asset valuation. Hence the various predictive and decision making models are likely to be more global in the case of network management planning with models representing the characteristics and behaviour of groups of structures. Consequently the type of data needed from associated sensor networks, communication and signal processing technologies to populate and continuously update these models would be different posing different challenges to their development and application.

Transportation Infrastructure Systems

There is a whole range of applications of the SmartEN integrated interdisciplinary technological developments in the area of smart transport infrastructure systems which encompass a more dynamic multidimensional environment with fixed and moving components requiring effective communication and interaction between them.

Furthermore, transportation infrastructure systems need to satisfy various objectives effectively including the need to move people, facilitate trade and shift commodities within nations and across borders. These need to be viewed against cost issues, rising security risks and users demanding easy and fast access. Clearly this is an area where integrated developments combining wireless sensor networks, communications and digital signal processing with predictive performance models, multi-objective optimisation and infrastructure reliability and management methods have a lot to offer. The types of developments proposed within SmartEN have the potential to move the area of smart transport infrastructure management forward with significant benefits for the future.

Urban Microclimate
SmartEN developments and applications in the area of urban microclimate will be of major significance and aim to contribute towards securing a diverse, healthy and resilient natural environment, which provides the basis for everyone's well-being, health and prosperity now and in the future; and where the value of the services provided by the natural environment are reflected in decision-making. Innovative wireless sensor systems and processes can be applied to ensure that: 1) the air that people breathe in cities are free from harmful levels of pollutants; 2) there is sustainable water use which balances water quality, environment, supply and demand; 3) the land and soils are managed sustainably 4) biodiversity is valued, safeguarded and enhanced sustainable, living landscapes with best features are conserved; 5) people are enjoying, understanding and caring for the natural and built environment.

6 Discussion and Conclusions

There are increasing concerns regarding the environmental impact of human actions, the use of the environment and deteriorating climate changes. These are coupled with ageing infrastructure systems, continuously growing and changing demands on the built and natural environments as well as limited financial and depleting natural resources. According to the EU COM(2004)60 "Towards a thematic strategy on the urban environment" buildings and the built environment uses 50% (measured by weight) of the materials taken from the Earth's crust. In addition waste produced from building materials, during the construction and demolition stages are the source of 25% of all waste generated in Europe. These issues pose significant challenges for designing and managing the human environment in a sustainable manner. Until now, research has been focused on the development of proactive risk-based approaches for civil infrastructure reliability and management with benefits in improved performance, safety and cost. However, there are significant uncertainties associated with the various predictive models directly affecting the quality of the decision making mainly due to the limited amount of information available on the condition, demands and actual performance of various systems.

Recently, a new generation of miniature wireless sensor platforms which utilize novel Digital Signal Processing, microprocessor and communication technologies has emerged. These can be adopted to obtain large quantities of highly diverse sensor data that are continuously collected over a long period of time from multiple targeted locations within a system therefore providing significant insight on the condition, demands

and performance of the system. These developments open up a completely novel area of multidisciplinary research and new research directions towards the 'smart' management of sustainable environment. Wireless Sensor Networks is a fast growing technology which can be widely used in a number of sectors associated with key aspects of the management of the human environment. There are significant opportunities presented in this area by the emerging technologies on wireless sensors and communications which can be exploited to develop dynamic and smart systems for strategic management.

Even though there are top research institutions around the world, which are focusing their activities in the development of WSN technologies and others that are focusing on civil infrastructure reliability and management research, most of the research activity is fragmented and there is not any significant activity in performing multidisciplinary, intersectoral structured research for developing integrated smart and dynamic systems for effective management of the built and natural environment. The aim of the 'SmartEN' ITN is to fill this technology gap and push innovation through the development of an initial research and training network that will focus its activities on the development and effective integration of emerging technologies in wireless sensors, communications and proactive management targeting key issues of current interest to the European Commission and internationally. These will include application areas in monitoring and smart proactive management of Structural Systems, Heritage and Infrastructure, Transportation Infrastructure Systems and Urban Microclimate.

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