Brussels, 12 February 2016

COST 026/16

DECISION

Subject: **Memorandum of Understanding for the implementation of the COST Action "Fractional-order systems; analysis, synthesis and their importance for future design" (FRACTAL) CA15225**

The COST Member Countries and/or the COST Cooperating State will find attached the Memorandum of Understanding for the COST Action Fractional-order systems; analysis, synthesis and their importance for future design approved by the Committee of Senior Officials through written procedure on 12 February 2016.

COST Association
Avenue Louise 149 I 1050 Brussels, Belgium
t: +32 (0)2 533 3800 I f: +32 (0)2 533 3890
office@cost.eu I www.cost.eu

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA15225
FRACTIONAL-ORDER SYSTEMS; ANALYSIS, SYNTHESIS AND THEIR IMPORTANCE FOR FUTURE DESIGN (FRACTAL)

The COST Member Countries and/or the COST Cooperating State, accepting the present Memorandum of Understanding (MoU) wish to undertake joint activities of mutual interest and declare their common intention to participate in the COST Action (the Action), referred to above and described in the Technical Annex of this MoU.

The Action will be carried out in accordance with the set of COST Implementation Rules approved by the Committee of Senior Officials (CSO), or any new document amending or replacing them:

a. "Rules for Participation in and Implementation of COST Activities" (COST 132/14);
b. "COST Action Proposal Submission, Evaluation, Selection and Approval" (COST 133/14);
c. "COST Action Management, Monitoring and Final Assessment" (COST 134/14);
d. "COST International Cooperation and Specific Organisations Participation" (COST 135/14).

The main aim and objective of the Action is to drive the European research and development in the field of description and implementation of fractional order systems in emerging fields of engineering and biomedical science, by overcoming the lack of common design and performance evaluation methods oriented on integer-order systems. This will be achieved through the specific objectives detailed in the Technical Annex.

The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at EUR 68 million in 2015.

The MoU will enter into force once at least five (5) COST Member Countries and/or COST Cooperating State have accepted it, and the corresponding Management Committee Members have been appointed, as described in the CSO Decision COST 134/14.

The COST Action will start from the date of the first Management Committee meeting and shall be implemented for a period of four (4) years, unless an extension is approved by the CSO following the procedure described in the CSO Decision COST 134/14.

COST is supported by the EU Framework Programme Horizon 2020
COST Association, International not-for-profit organisation/Association internationale sans but lucratif
Register of legal Entities Brussels: 0829090573
COST Association
Avenue Louise 149 I 1050 Brussels, Belgium
t: +32 (0)2 533 3800 I f: +32 (0)2 533 3890
office@cost.eu I www.cost.eu

TECHNICAL ANNEX

OVERVIEW

Summary

Fractional-order systems have lately been attracting significant attention and gaining more acceptance as generalization to classical integer-order systems. Mathematical basics of fractional-order calculus were laid nearly 300 years ago and since that it has gained deeply rooted mathematical concepts. Today, it is known that many real dynamic systems cannot be described by a system of simple differential equation or of integer-order system. In practice we can encounter such systems in electronics, signal processing, thermodynamics, biology, medicine, control theory, etc. The Action will favour scientific advancement in above mentioned areas by coordinating activities of academic research groups towards an efficient deployment of fractal theory to industry applications. The cooperation of researchers from different institutions will guarantee wide visibility of Action results.

Areas of Expertise Relevant for the Action	Keywords
● Electrical engineering, electronic engineering, Information engineering: Signal processing, 1-D and multidimensional signal processing, compression, signal acquisition ● Electrical engineering, electronic engineering, Information engineering: Simulation engineering and modelling ● Mathematics: Theoretical aspects of partial differential equations ● Health Sciences: Applied mathematics, statistics, non-computational modeling for health sciences	● Fractional calculus, modelling and approximation ● Fractional-order elements, analogue/digital blocks ● Optimal control ● FO systems in biomedicine

Specific Objectives

To achieve the main objective described in this MoU, the following specific objectives shall be accomplished:

Research Coordination

● Define optimization steps leading to efficient implementation of fractional-order systems
● Improve characteristics of fractional-order controllers that can be employed in different industrial loops or in electro-mechanical systems
● Develop tools to define dynamic simulation models, control schemes and algorithms
● Design and implement fractional-order controllers for industrial processes
● Design and characterize new fractional-order elements using prospective technologies in order to obtain robust and commercial devices
● Utilize fractional-order adjustment rule to model reference adaptive control in engineering applications
● Implement fractional-order digital/analogue function blocks especially in medical signal processing
● Utilize fractional-order models and systems in bioengineering and biomedical applications
● Characterize preservation properties of non-integer order control and dynamical systems under discretization

Capacity Building

● Establishment of European-wide scientific and technology knowledge platform in order to instigate interdisciplinary interaction for the development of innovative fractional-order systems
● Bridging separate research fields and disciplines to present interdisciplinary approach to scientific research and foster multidisciplinary breakthroughs
● Ensure Early Career Investigators to participate in the Action within dedicated dissemination and formation activities such as workshops or STSMs and give them the best possible return in terms of

scientific knowledge, research direction and coordination skills

● Increase the gender balance in terms of researchers involved in Action activities, both in terms of technical and scientific contribution as well as of research direction and Action governance

COST Association
Avenue Louise 149 I 1050 Brussels, Belgium
t: +32 (0)2 533 3800 I f: +32 (0)2 533 3890
office@cost.eu I www.cost.eu

DESCRIPTION OF THE COST ACTION

1. S&T EXCELLENCE

1.1. Challenge

1.1.1. Description of the Challenge (Main Aim)

It has become evident that mathematical modelling can be very useful for solving virtually all real world problems on the condition that an adequate mathematical model can be developed, identified and later implemented in practice. A quest for the improved models leads to the introduction of so-called non-integral systems, also known as fractional systems, described by differential equations of non-integer order. Such systems currently attract an increasing attention in the scientific community as they can be both theoretically challenging and relevant for many fields of science and technology. Based on that, the theory and usage of fractional-order (FO) calculus gains a rapid momentum due to its effectiveness in dynamic system modelling, analysis and design. In practice we can encounter such systems not only in electronics and signal processing (both continuous and discrete), but also in thermodynamics, biology, chemistry, medicine, mechanics, control theory, nanotechnologies, economy etc.

Although the theoretical description of fractional systems can be found in the literature, the number of in-hardware realized function blocks that could be used in practice is still very limited and hence requires to be carefully investigated. The reason of slow encouraging attention of engineers and designers can be seen in the fact that a practical and reliable solid-state element with fractional-order immittance is not available at the moment. The circuit designers use various ways to overcome this absence, such as approximate a fractional order element by an integer order structure, which is neither economic nor practical as the complexity of the final structure increases. The challenge is to efficiently implement fractional-order blocks both in digital and analogue systems.

Another challenge is using fractional order systems for bioengineering and biomedical applications related to modelling diffusion of tumours and to early diagnosis. In particular, it is known that biological media and tissues add significant complexity because their relative complex permittivity includes non-integer (fractional) powers of the frequency-domain differential operator (jω) to properly represent the dispersive nature. An integro-differential equation of fractional order can be derived to describe the time-domain electro-magnetic behaviour of the considered media. In the area of biomedicine, fractional order modelling can be advantageously applied for capturing pain pathways during anaesthesia that plays a key-role in today's society through healthcare management. Current patient models, which take into account physical aspects, drug pharmacokinetics and pharmacodynamics providing better drug dosing are based on classical (integer-order) functions and classical derivatives. However, the use of emerging non-classical concepts of fractional derivatives, functions and impedance models shows advantageous features in biomedical applications.

The FRACTAL Action will tackle the above mentioned issues by addressing the following challenges:

- Achieve the scientific and technical breakthroughs required for the definition of accurate, reliable models of fractional-order dynamic systems;
- Develop fractional-order models describing biological systems;
- Increase the approximation accuracy, mainly at very low and very high frequencies;
- Implement fractional-order systems on digital signal processing cards by using embedded programming techniques;
- Develop analogue fractional-order structures designated for circuit design, actuators and sensors;

- Real-time application in control and filtering

1.1.2. Relevance and timeliness

Non-integer (fractional) order derivatives have been studied by mathematicians since the late seventeenth century, where Leibniz, de L'Hospital, Riemann, Liouville and others were involved in their early development. However, first the recent decades show a surge in interest caused by the potential applications that can be introduced using fractional systems. The reason is the fact that they have proven their power as an effective and efficient tool for modelling of various processes and systems in the areas of physics, chemistry, biology, electrical engineering, control etc. Fractional systems became especially interesting because of their frequency response properties that spark interest especially in the field of robust control. However, the problem of implementation became highly significant. The implementation problem led to the presentation of various approximation methods that, however, result in relatively complex integer order systems with sufficient approximation accuracy only in a narrow frequency range. The problems of approximations that can be properly discretised are relatively open in the context of fractional systems. Also the problems of stability of non-integer order systems are less investigated. There are methods similar to classical linearization but very little interest is given to e.g. Lyapunov like methods, which have a significant potential in applications.
As mentioned in Section 1.1.1, one of the current challenges is to design and develop analogue fractional order structures as discrete elements suitable for circuit design, actuators and sensors. Recently, the use of resistive-capacitive elements with distributed parameters (RC-EDP) has shown to be suitable for the design of fractional-order electronic elements (FOEs). These elements based on special geometrical and technological inhomogeneities in resistive and capacitive layers are fractional-order elements by their nature. Moreover, they are easily integrable and their properties can be digitally adjusted e.g. by switching transistors. Next to RC-EDP, the Ionic polymer-metal composites (IPMCs) as electroactive polymers have shown very interesting capabilities of transforming electrical energy into mechanical energy and vice versa. The possibility of modelling the IPMC actuators using fractional order systems has been presented, which paves the way for a brand new approach to such materials seen as fractional-order electronic elements. This presumption is suggested by IPMC electrochemical and structural properties, since the dendrites on the interfacial landscape between the metal electrodes and the polymer layer show fractal dimensions.
The fractional order operators have remarkable features that may be exploited also in the design of function blocks for biomedical applications, signal and image processing.

1.2. Specific Objectives

1.2.1. Research Coordination Objectives

The primary goal of FRACTAL is to drive the European research and development in the field of description and implementation of fractional order systems in emerging fields of engineering and biomedical science, by overcoming the lack of common design and performance evaluation methods oriented on integer-order systems. A European-wide scientific and technology knowledge platform will be formed in order to instigate interdisciplinary interaction for the development of innovative fractional-order systems.
The FRACTAL Action will achieve this goal by pursuing the following set of objectives:
- Definition of optimization steps leading to efficient implementation of FO systems,
- Improving characteristics of fractional-order controllers that can be employed in different industrial loops or in electro-mechanical systems,
- Development of tools to define dynamic simulation models, control schemes and algorithms,

- Design and implementation of FO controllers for industrial processes,
- Design and characterize new FOEs based on IPMC, graphene oxide percolated polymer composites and elements with distributed parameters in order to obtain robust and commercial devices,
- Utilization of fractional-order adjustment rule to model reference adaptive control in engineering applications,
- Implementation of fractional-order digital/analogue function blocks especially in medical signal processing,
- Penetration of the fractional-order models and systems in bioengineering and biomedical applications related to medical treatment, surgical interventions, drug delivery problems etc.
- Characterization of properties preservation of non-integer order control and dynamical systems under discretization; new types of variational integrators.

FRACTAL will maximize both short and long term impact of the Action activities by pursuing a comprehensive dissemination of research results to all relevant stakeholders. For details on how the stakeholders are involved and how the dissemination objectives are pursued, see Section 2.

1.2.2. Capacity-building Objectives

The accomplishment of research coordination objectives described in Section 1.2.1 will be achieved by using the current expertise in the different research communities involved in the Action, and by creating and sharing new knowledge as a result of the exchange between them.

The Action will support and extend coordination efforts put in place by the EU by pursuing an interdisciplinary approach. FRACTAL will allow a significant leap in the quality and effectiveness of the European research, by filling the gap between the research communities involved in the broad context of fractional-order calculus, system description, modelling, design and implementation. FRACTAL will take special care to ensure that Early Career Investigators (ECIs) participating in the Action activities will have the best possible return in terms of scientific knowledge, research direction and coordination skills. ECIs will be put in contact with the major experts in the field, thanks to dedicated dissemination and formation activities. The ECIs will be also encouraged to propose Short Term Scientific Missions (STSMs) to research teams active in different areas, favouring the development of an interdisciplinary approach to scientific research, and also forstering gender balance. The FRACTAL will also set as a high priority objective the involvement of female researchers in Action activities, both in terms of technical and scientific contribution and of research direction and coordination, by favouring access of female researchers to leading roles in Working Groups (WGs).

1.3. Progress beyond the state-of-the-art and Innovation Potential

1.3.1. Description of the state-of-the-art

To solve virtually all real world problems, an adequate mathematical model must be developed, identified and finally implemented into a system. Hence, it is clear that the mathematical modelling is very useful and vital to describe, design and control new systems and/or processes.

Based on the mathematical description of any system or function block, they are traditionally classified to be of first, second, or n-th order, whereas n is an integer number and the system's behaviour is defined using integer-order differential equations. However, it is also mathematically valid to evaluate fractional-order differential equations and hence to describe a fractional-order (also fraction) system. In practice, it has been shown that using fractional-order approach is more advantageous in terms of modelling and control point of view, whereas FO systems might help finding compact representations of complex dynamics that cannot be easily described by other linear or non-linear modelling tools and FO controllers might provide a flexible and performing solution that

is a good trade-off between superior robustness and ease of tuning and implementation. The research topic is of great current interest, since it means qualitatively new and higher level of modelling and control of real objects and processes. This explains why recently this field has drawn attention of many top world research institutions, which focus on the most important problems of science, engineering and technology. Currently in the area of mathematical description, the attention of the world research community working in this field turns towards further generalisations of differentiation and integration, namely on differentiation and integration of variable order (non-integer that depends on time or on a controlled parameter – “variable-order differentiation”) and distributed order (“distributed-order differentiation”).
Once describing the systems using fractional calculus, the final implementation of fractional-order models and controllers is an issue. The digital implementation is seen to be of high importance . The major problem however, is the stability of such implementations due to the rounding problems. Therefore, also analogue implementation of fractional systems is considered as desirable design procedure. Although reliable solid-state FOEs with fractional-order immittance are not available at the moment, circuit designers overcome this absence by approximating fractional-order capacitors or inductors by suitable structures or they are experimentally implemented by various chemical or biological materials. Also the continued fraction expansion (CFE) method can be used to implement the required FOE. However, such approximation techniques are not neither economic nor practical as the complexity of the final structure increases.
The fractional order calculus has shown to be a very useful tool to describe also natural and/or biological phenomena. Recent research activities are on modelling and simulation of Havriliak - Negami systems that can be helpful to describe electro-magnetic field’s propagation in dispersive media and biological tissues. The Havriliak-Negami models allow a more general and realistic description of the interactions between electric and magnetic field, as well as the induced polarization, in biological tissues so that diagnostic imaging and tumour treatment can be more efficient. In biomedical engineering area the fractional order impedance systems (FOIMs) have shown their potential to model and characterize the drug diffusion processes as well as neural transmission patterns. Such tools can be advantageously applied to biological processes, such as general anesthesia, motivated by the fact that diffusion mechanisms are naturally described by fractional-order derivate functions.

1.3.2. Progress beyond the state-of-the-art

Although the Havriliak-Negami relaxation has been widely investigated in the frequency-domain, time-domain simulation is still challenging. Namely, unlike other simpler models (Debye and Cole-Cole) for which a representation in the time-domain is possible in terms of integer and fractional-order differential equations and hence standard techniques for numerical integration can be applied. There is no standard formulation of the Havriliak-Negami time integral or differential operator. Therefore, the new efficient representations for the fractional pseudo-operators involved in Havriliak-Negami models are to be investigated, their main theoretical properties studied and mainly accurate and efficient numerical schemes for their use in numerical applications devised.
As mentioned, approximating fractional order elements by integer-order structures is not suitable from the viewpoint of practical implementation due complexity. Innovative solutions in efficient design of FOEs applied in analogue fractional order circuit structures may lay in the usage of resistive-capacitive elements with distributed parameters or ionic polymer-metal composites that have shown fractal dimensions.
Many of the results presented by the members of the Action proposers’ network in the field of fractional - order derivatives and fractional-order differential equations have the world priority. This gives the Action the chance to achieve a similar position also in the field of applications.

1.3.3. Innovation in tackling the challenge

The FRACTAL Action constitutes indeed a significant innovation compared to all existing efforts by its interdisciplinarity. In the framework of FRACTAL, the innovative contributions following the challenges are expected in the improvement of existing methods or development of new ones for solving differential equations of non-integer order. Based on these results, approximation accuracy will be increased and the new types of controllers and systems described by variable-order and distributed-order operators will lead to the definition and description of advanced models of real processes and systems. For real applications, using embedded programming techniques the fractional-order signal processing components will be developed, optimized and utilized in medical signal processing, biomedical and technical engineering. In order to obtain robust and commercial devices, the design and characterization of new IPMC and/or graphene oxide percolated polymer composites and RC-EDP based FOEs are also the innovative results tackling the challenges of FRACTAL. Using the designed FOEs, next to digitally implemented fractional order systems, original analogue fractional order function blocks, actuators and sensors suitable for real-time applications in control and filtering will be defined.

1.4. Added value of networking

1.4.1. In relation to the Challenge

The existence of large-scale research efforts already in place spanning a wide range of research areas and involving institutions and researchers from different communities calls for an interdisciplinary approach for the coordination of such efforts, to guarantee an efficient use of the resources allocated in Europe and worldwide. The COST scheme is uniquely suited to achieve this goal, as its primary aim is to favour networking and coordination of existing research efforts. The FRACTAL will leverage all the networking instruments offered by the COST framework:
Organization of annual workshops and public events – Workshops and events will be organized whenever possible in conjunction with major conferences and workshops dedicated to FO calculus, circuits and systems, modelling, control and biomedical engineering in order to optimize the use of resources, and guarantee the maximum visibility of project activities. These events will be crucial in building the FRACTAL research community.
WG meetings – Meetings support by COST will allow researchers to meet, interact, establish new connections and develop joint research ideas. Joint meetings will be held regularly, but ad-hoc WG meetings focusing on specific scientific issues will be encouraged.
Short Term Scientific Missions – STSMs will allow ECIs to spend extended periods of time at host institutions in order to complete their formation, and will be used as a tool to focus on specific scientific activities, for example towards a joint publication. In order to simplify the access to this tool, an STSM manager will be elected and included in the Core Group (CG, see Section 3.2).

1.4.2. In relation to existing efforts at European and/or international level

Research topics within the scope of FRACTAL are of great current interest, as they significantly contribute to new and higher level modelling and control of real objects and processes. Dealing with the tasks of this Action comply with recent attention of many top world research institutions mentioned in Section 1.3.1.
The issue of modelling of various systems has been addressed by the DANSE project, where e.g. traffic management or water treatment and supply has been handled. The approach of using fractional order differential equation can be seen as a continuation to more accurate description, modelling and approximation of various phenomena.

COST Association
Avenue Louise 149 I 1050 Brussels, Belgium
t: +32 (0)2 533 3800 I f: +32 (0)2 533 3890
office@cost.eu I www.cost.eu

The issue of fractional calculus has been also addressed in the project LEFRAC, that has been focused on development of new probabilistic and physical kinetics methods for the studies of anomalous transport and relaxation phenomena in complex non-equilibrium systems.
This Action follows the idea of the COMPASS project aiming to bring together mathematics and science. Such connection is evident also in FRACTAL, its proposers are active both in theoretical fractional calculus, mathematical modelling and in engineering and biomedical areas.
There is no existing Action addressing the area of fractional systems, their description, design and utilization in complex function blocks. Supporting the activities of FRACTAL will create a wide interdisciplinary research community allowing young researchers to meet experienced ones and to be part of their research activities.

2. IMPACT

2.1. Expected Impact

2.1.1. Short-term and long-term scientific, technological, and/or socioeconomic impacts

Once mathematical modelling is seen as a powerful tool to describe the real world problems a quest for better, more accurate, more efficient and more suitable mathematical description is obvious. From the wide array of various models and mathematical theories the impact of FRACTAL is in the increase of effectiveness of resources and efforts allocated in Europe and the neighbour partner countries in the area of fractional order calculus and its advantageous application in many fields of science and technologies, which is reached by tighter interaction between research communities working on the different research topics, and better mutual visibility and exchange of results among active projects funded by other funding in struments such as Horizon 2020.
Scientific, industrial, economic and social benefits are expected as a result of Action activities. From a scientific point of view, technical advances on all relevant topics identified in Section 1.3 will be achieved, whereas strong positive impact on European research can be expected. From an industrial and economic point of view, the dynamic simulation models, control schemes and algorithms, and hardware solutions for engineering and biomedical areas will be available.

2.2. Measures to Maximise Impact

2.2.1. Plan for involving the most relevant stakeholders

The most relevant stakeholders for the topics addressed by FRACTAL can be identified as follows:
- The scientific communities working on research topics relevant to the objectives of FRACTAL, which will leverage the networking tools made available by COST in order to achieve otherwise unreachable scientific breakthroughs, as well as researchers from the other fields that are related to the scientific issues faced in this Action.
- Industry players active in the fields of machine and/or system control and modelling, signal, image and video processing not limited to bioengineering and biomedical applications.
The Action will proactively involve stakeholders as a result of the extensive dissemination plan described in Section 2.2.2.

2.2.2. Dissemination and/or Exploitation Plan

The Action will prepare a detailed dissemination plan that will be revised and updated on a yearly basis, taking into account the natural evolution of Action activities as well as the outcome of the assessments of the Action's achievements. Variations in budget allocation, for example due to the new countries signing the MoU (Memorandum of Understanding), will be reflected in the

dissemination plan as well. The obtained results of this Action will be disseminated using the following methods:
- *Action website* - a website for the Action will be set up after the kick-off meeting. This website will be the portal of the Action towards the external world, providing information about the Action's activities, organization, and scientific and technical results. In addition, it will serve as an internal database for Action participants, providing access to Action documents, STSM reports and WG technical reports and to a private discussion forum to be used for organizing Action initiatives.
- *Use of social networks* - together with the activation of the Action website, FRACTAL will establish its presence on the major social platforms, such as Facebook, Twitter, LinkedIn, or Google+.
- *Workshop* - The Action will organize a Workshop (WS) at the end of each year, co-located with the Action meeting. The WS will be an open event, whereas the invitations will be issued to companies and public entities potentially interested in FRACTAL activities. Discussion sessions and panels will contribute to the interaction between speakers and audience. In order to ensure that Action scientific results are prepared and presented carefully, a call for contributions by ECIs will be issued before each WS, offering travel reimbursement to selected authors. In addition, to foster ECIs to present their work in a clear and engaging manner, awards will be assigned to the best presentations. Proceedings of each WS will be made available on the Action website after the event.
- *Conference special sessions* - Communicating with conference organizers, special sessions dedicated to the topics relevant to FRACTAL activities will be proposed in international conferences.
- *Seminars and courses* - In addition to the annual WS, the organization of short tutorials and training lectures to be offered to ECIs and experts in the framework of WG meetings will be encouraged, in order to maximize the transfer of knowledge among researchers.
- *Publications* - The Action will encourage joint publications between partners and participation in international events relevant to the Objectives.
- *Internal technical reports* - Project partners will be encouraged to create internal technical reports describing scientific results and their progress. These reports will be used as basis for the preparation of joint journal and conference papers.
- *Annual reports* - Annual reports, presenting scientific advancements, major findings and results produced by the WGs will be published on the Action's website. The first Workshop Report (M12) will contain an extensive state-of-art review on all the major research topics, followed by two reports at M24 and M36 describing the progress, and finally by the last report (M48) containing the conclusions and major deliverables of the Action.
- *Action Book* - The most relevant works presented in the WSs will be selected to edit a final Book, summarizing Action activities and scientific results achieved during its four years span, with WG leaders, jointly with Action Chair and Vice-Chair, serving as editors.
The Action will ensure that all above listed dissemination methods are properly addressed and implemented during and after the Action period. In particular, the impact of the website will be assessed by monitoring number of accesses and page visits. The results of the assessment activities will be included in the yearly Action progress report.
Despite the final goal of the Action being to define open, shared solutions, it is reasonable to expect the creation of joint Intellectual Properties (IP). The Action will support the definition of agreements that favour the adoption and spread of the ideas generated as a result of FRACTAL activities while guaranteeing fair conditions and recognition of IP rights to the partners, who are interested.

2.3. Potential for Innovation versus Risk Level

2.3.1. Potential for scientific, technological and/or socioeconomic innovation breakthroughs

COST Association
Avenue Louise 149 | 1050 Brussels, Belgium
t: +32 (0)2 533 3800 | f: +32 (0)2 533 3890
office@cost.eu | www.cost.eu

The Action will engage all stakeholders towards tackling the challenges to reach the ambitious goals of FRACTAL that will constitute the main deliverables of this Action. The achievement of these results will require a strong commitment of researchers, institutions and projects to FRACTAL activities, which can be considered a potential point of failure, whereas this risk is characteristic for the COST approach itself. However, the success of the FRACTAL will significantly contribute to the efficient application of fractional-order approach to interdisciplinary research, innovation and industry areas not only in terms of the advanced technical features offered by the FO systems and function blocks, but also of their social impact, and this fully justifies the risks taken in funding the Action.

3. IMPLEMENTATION

3.1. Description of the Work Plan

3.1.1. Description of Working Groups

The Action duration is 4 years, a period adequate to achieve research results and create solid links among partners. The Action activities will be organized in four Working Groups (WGs).

<u>WG1 - Fractional calculus and mathematical models</u>
WG1 will improve existing and develop new methods for solving non-integer differential equations. WG1 will also provide an application oriented view on the theory of fractional equations to model the behaviour of various function circuits, control, and to describe the processes investigated within other working groups. The activities of WG1 are divided into the following tasks:

- Task 1.1 Mathematical methods of fractional order integration and differentiation

The effort within the frame of this task will focus on enhancement of existing and development of new numerical and analytical methods for approximation of derivatives and integrals of fractional orders, variable orders, and distributed orders, and methods for solving ordinary and partial differential equations with derivatives of all these types. By research in this new field hypothesis that variable-order and distributed-order integrals and derivatives will provide higher level of adequacy of the created mathematical models of real processes and dynamical systems in principle without increasing complexity of the structure of such models is to be proven.

- Task 1.2 Fractional order controllers

For fractional-order systems the various kinds of the fractional-order controllers have been developed, e.g. CRONE, PD-delta controller and the PI-lambda-D-mu controller. Yet another improvement of the PID controller will arise using the variable-order and distributed-order differ-integrals. A variety of novel controllers will be studied containing such integer and non-integer operators. The synthesis of a controller is based on parameters determination according to the given requirements, for example, the stability measure, the accuracy of the regulation process, dynamical properties etc. The verification whether the requirements have been met will be done within the tasks of WG3 and WG4 using both computer simulations and analogue as well as digital controllers' realisations based on the use of variable-order and distributed-order operators.

- Task 1.3 Parameter estimation and modelling of real processes and systems

In order to utilize the full power of fractional calculus in providing more feasible description of physical systems, it is necessary to develop associated efficient and robust modelling and identification techniques. General framework that will cover rational, fractional and general non - rational systems, including systems with input and state delay, distributed -parameter and distributed-order systems will be considered, whereas two classes of such techniques: global off- line estimation methods and local, on-line, adaptive ones are to be investigated. Modern evolutionary or swarm-based techniques could be used for identification, such as Particle Swarm Optimization and its numerous variations. When dealing with adaptive methods, we will focus on the cases when only small amount of recent measurements are available and the computational load must be reduced to minimum. Gradient-based methods, and method obtained by hybridization of gradient and recursive least squares will be pursued in this context.

- Task 1.4. Developing efficient and accurate numerical schemes

One of the key issues with fractional-order differential equations is the design of efficient numerical schemes for the space and time discretizations. Until now, most models have relied on the finite difference method to discretize both the fractional-order space diffusion term and time derivative. Some numerical schemes using low-order finite elements have also been proposed. Unified derivation of the discrete models equations for each of these methods will be provided and numerical schemes efficiency can be impaired when discretizing the fractional diffusion term will be determined. The numerical examples that highlight the convergence rate and computational cost of the different methods will be provided.

- Task 1.5 Development of toolboxes for MATLAB

MATLAB belongs to one of the leading environments for performing scientific calculations, but also for the control system design, so naturally it will be used to create toolboxes in the frame of this Action. The toolboxes will contain set of routines solving the problems under study, e.g. they will provide the tools for numerical simulations of dynamical systems and control systems of non- integer orders. Implementation of parallel algorithms into existing toolboxes and development of new ones for variable- and distributed-orders will be performed. All prepared routines will be published on the website MATLAB Central File Exchange maintained by MathWorks, Inc., the makers of MATLAB, and so they will be free to download for the scientific community, who can use these for experiments and extended research in many fields.

- Task 1.6 Fractionalizing standard models

The success of models based on fractional-order differential equations stems from the observations that complex systems often exhibit a diffusive behaviour that departs from ordinary diffusion and Brownian motion. Such behaviour has been observed in the mobility patterns of living organisms including humans, animals and cells, in the dynamics of a drug in the body, or even in financial time series, in the hydrological data. It has been shown that to simply replace integer derivatives by fractional ones can have important consequences as e.g. from a physical point of view as some terms, like input functions cannot have fractional dimensions. We propose to focus on each of the flux terms in the right-hand side of the equation and fractionalize them on a one-by- one basis. Doing so, it will be possible to distinguish between the different processes at play and fractionalize only the ones that indeed have an anomalous dynamics without affecting the others . The issues solved within this task are particularly important in models used in pharmacokinetics, epidemiology and other fields related to biomedical sciences and in within the activities of WG4.

- Task 1.7 Investigation of preservation of properties of non-integer order control and dynamical systems, characterizations and algorithms under discretization

Continuous-time and discrete-time systems behave in a very different way and finding a common characterization may be a challenging problem. Several problems such as controllability, stability, positivity, linearization and observability problems will be stated. The attention will be paid to discretizing Hamilton’s principle of stationary action and the fractional variational principle.

The deliverables of WG1 can be summarized as follows:

No.	Title	Description	M.
D1.1	Off-line identification	Development and implementation of a general framework for global, non-adaptive identification of fractional and non-rational systems in general	10

D1.2	Y1 WS proceedings	Contribution by WG1 to the proceedings of Year 1 WS	12
D1.3	Adaptive identification	Development and implementation of a general framework of adaptive identification of fractional and non-rational systems	20
D1.4	Y2 WS proceedings	Contribution by WG1 to the proceedings of Year 2 WS	24
D1.5	FO methods and models	Approximation of derivatives and integrals of fractional orders by new numerical and analytical methods; Fractionized models	36
D1.6	Y3 WS proceedings	Contribution by WG1 to the proceedings of Year 3 WS	36
D1.7	Discrete FOs	Development of methods for PID controllers' synthesis, Matlab toolboxes, discretization algorithms	46
D1.8	Y4 WS proceedings	Contribution by WG1 to the proceedings of Year 4 WS	48
D1.9	Action book input	Contribution by WG1 to the final Action book	48

WG2 - Fractional-order systems' synthesis and analysis

WG2 will focus on overcoming the lack of reliable solid-state elements featuring fractional-order immitance suitable for hardware realizations of analogue function blocks. In parallel, activities within this WG are the presentation of tools suited for fractional-order function blocks symbolic and semi-symbolic analysis and description. The activities of WG2 are divided into the following tasks:

- Task 2.1 Synthesis of fractional order elements

Very accurate modelling of fractional order impedances based on typical passive elements will be proposed, there in the initial phase the fractional-order capacitors and fractional-order inductors will be approximated using RC and LR ladder structures. This approach is useful to keep the number of active elements in the circuit structure low, and generally enables to use the known integer - order circuit solutions. Later, the activities within this task will focus on the employment of resistive - capacitive elements with the distributed parameters (RC-EDP) that based on specific geometrical and technological inhomogeneities in resistive and capacitive layers feature fractional -order immittances. Also new fractional order electronic elements based on IMPC and graphene oxide percolated polymer composites will be characterised and designed in order to obtain robust and commercial devices.

- Task 2.2 Numerical methods for simulation of fractional order systems

In the analogue circuit theory, the methods enabling analysis of function blocks being designed will be developed. The proposed analysis methods will be based on integer-order systems' description. Such methods are expected also to be advantageously used for the synthesis needs, as it is the case of signal-flow graphs when designing integer order systems.

- Task 2.3 Approximation of fractional order blocks

This activity stems from the fact that fractional-order circuit function can be approximated by a suitable integer-order function. Classic circuit design and analysis tools are based on integer-order differential equations and these tools can be advantageously applied when the non-integer power of Laplacian operator if required. The task is to develop optimal and increase the accuracy of low- order approximations of fractional Laplacian operator by presenting the own solutions while observing other important circuit design requirements, such as circuit simplicity, easy integrability, electronic tunability, low power consumption etc. In order to simulate fractional-order systems on a digital computer, it is necessary to develop suitable discrete rational approximations. Using the experience of the network members, more accurate and efficient approximations including those specialized for particular purposes will be developed. Achieving high accuracy when approximating general fractional and non-rational systems the issue of memory requirements, not prone to computational errors and reduced computational demands will be also addressed.

The deliverables of WG2 can be summarized as follows:

No.	Title	Description	M.
D2.1	Low-order approximations	Presentation of optimized low-order approximations	10
D2.2	Y1 WS proceedings	Contribution by WG2 to the proceedings of Year 1 WS	12
D2.3	FO analysis tools	Presentation of tools for fractional-order function blocks analysis and synthesis	22
D2.4	Y2 WS proceedings	Contribution by WG2 to the proceedings of Year 2 WS	24
D2.5	Accurate approximations	Increased approximation accuracy of fractional Laplacian operator, discrete rational approximations	36
D2.6	Y3 WS proceedings	Contribution by WG2 to the proceedings of Year 3 WS	36
D2.7	New FOEs	Presentation of new IMPC, graphene and RC-EDP FOEs	45
D2.8	Y4 WS proceedings	Contribution by WG2 to the proceedings of Year 4 WS	48
D2.9	Action book input	Contribution by WG2 to the final Action book	48

WG3 - Design of analogue and digital fractional-order function blocks

In close cooperation with WG2 and using their deliverables, the activities of WG3 focus on the design of reliable fractional-order function blocks suited for signal processing and control, synthesised both in analogue and digital form. The activities of WG2 are divided into the following tasks:

- Task 3.1 Fractional order analogue filters

Building blocks for implementing analogue fractional-order filters, including lossy and lossless integrators and differentiators, will be developed by employing the FOEs developed within the Task 2.1. Appropriate active elements will be used, in order to fulfil the requirements for circuit simplicity, easy integrability, electronic tunability, low power consumption etc. Another goal is to develop fractional-order filters, which will offer electronic programmability of their behaviour. The performance of the proposed fractional-order filter structures will be compared to already published solutions where integer-order approximation has been utilized, at the expense of circuit complexity and power dissipation, in order to show the benefits offered by the proposed schemes. These filters find their utilization e.g. in biomedical applications within WG4, to handle noisy electrocardiogram signals in systems that implement the well-known Pan-Tompkins algorithm for detecting the QRS complexes of an electrocardiogram. Other targeted applications could be in actuators and sensors, as well as in control systems.

- Task 3.2 Fractional order digital filters

This task aims to implement fraction-order signal processing of medical signals by using embedded programming techniques. To implement fractional order signal processing components a suitable DSP cart will be used. Depending on features of DSP card, developed code for embedded programming should be optimized to meet the requirements of real applications. First fractional-order digital filter design tool and validation of the results of implemented filter blocks will be developed and followed by experimental setup, DSP card coding, testing and validation activities.

- Task 3.3 Optimal control

Dynamic programming problems for fractional time-invariant and time-varying discrete-time systems with quadratic performance index will be formulated and solved. The new methods for solution and numerical computation of optimal dynamic control will be presented. The efficiency of the methods will be validated and demonstrated on numerical examples. The similarities and differences between the fractional and standard (integer-order) systems theory will be discussed. The results for different systems and different order for both invariant and varying systems will be taken into consideration. The methods will be simulated using MATLAB algorithms and toolboxes prepared in cooperation with WG1, Task 1.5.

- Task 3.4 Design of non-linear analogue function blocks

Using the synthesised FOEs and design methods defined within WG2, the task is to design non-linear function blocks suitable for analogue signal processing. With advantage also the results reached within Task 2.3 will be used.

- Task 3.5 Digital fractional-order controllers

This task involves implementing digital fractional-order controllers on embedded hardware for industrial applications using methods developed within WG1 and WG2. Particular attention is given to correct fulfilment of frequency-domain specifications as well as long-term stability considerations.

The deliverables of WG3 can be summarized as follows:

No.	Title	Description	M.
D3.1	Basic analogue and digital FO blocks	Development of integrators and differentiators, Initial implementation of digital blocks	10
D3.2	Y1 WS proceedings	Contribution by WG3 to the proceedings of Year 1 WS	12
D3.3	FO filters	Development of FO analogue and digital filter topologies using the building blocks of D3.1	23
D3.4	Y2 WS proceedings	Contribution by WG3 to the proceedings of Year 2 WS	24
D3.5	Optimal dynamic control	Methods for solution and numerical computation of optimal dynamic control	34
D3.6	Y3 WS proceedings	Contribution by WG3 to the proceedings of Year 3 WS	36
D3.7	Sensors, actuators and control systems	Application of FO linear and non-linear blocks in sensors, actuators and control systems.	46
D3.8	Y4 WS proceedings	Contribution by WG3 to the proceedings of Year 4 WS	48
D3.9	Action book input	Contribution by WG3 to the final Action book	48

WG4 - Utilization of fractional-order systems in engineering and biomedical research areas

All the activities and results reached within WG1, WG2 and WG3 are advantageously used to utilize the fractional order systems in applications rising from engineering and biomedical areas. The new observations in solving non-integer differential equations, proposed circuits and complex function blocks, control systems are employed to solve following tasks:

- Task 4.1 Automotive applications

This task contributes to the challenge of conjugating the satisfaction of growing requirements with specified levels of performance indices and with the capability to react to the environmental changes. The activities focus on innovative injection systems and on innovative technologies for reducing pollution and consumption in internal combustion automotive engines. In particular, the aim is to improve current technology employed in advanced Diesel engines or compressed natural gas engines. The work will partly rely on the outputs of Task 1.3, by extending the research results on parameter estimation of innovative engines, and on the outputs of Task 2.3.

- Task 4.2 Electro-magnetic fields in biological tissues: applications to diagnosis and therapy of tumours

Using fractional-order systems the task is to model electromagnetic fields in biological tissues, in particular for applications to diagnosis and therapy of tumours. Also the goal is to investigate new efficient representations for the fractional pseudo-operators involved by Havriliak-Negami models, to study their main theoretical properties, and, with major emphasis, to derive accurate and efficient numerical schemes for their use in numerical simulations.

- Task 4.3 Fractional order adjustment rule for model reference adaptive control

The task is to implement a fractional order adjustment rule-model reference adaptive control (FOAR-MRAC) by using embedded programming techniques, which enables to solve such engineering problems encountered in the implementation of FOAR-MRAC in control engineering applications. The developed FOAR-MRAC structure will be utilized it in adaptive control of real systems.

- Task 4.4 Modelling of capturing pain pathways during anesthesia

The task consists of developing: i) a micro-scale model for transduction using gate control theory (GCT) and ii) a macro-scale model of transmission based on neuron population models and analogy to electrical ladder networks. To achieve this objective, an analysis of the necessary elements at cellular level of analgesic drug effect in the body using GCT and ion -channel theory will be investigated. The tools from fractional calculus will be employed since fractional-order derivative models are a natural solution for diffusion phenomena. Finally, electrical ladder networks will be used for capturing memory effects through the fractional-order impedance with constant phase elements.

- Task 4.5 Fractional-order models of the human respiratory system

Here we explore the opportunities of applying fractional calculus tools and non -invasively detect the viscoelastic properties in the respiratory tissues. We have shown that respiratory system is a natural candidate to be modelled using fractional order impedance models (FOIMs), while preserving anatomy, structure and physiology of the respiratory airways and tissues. A correlation analysis will be made between structural changes in pathology and its effect in the impedance model parameters of the respiratory tract.

- Task 4.6 FO modelling and control of swimming microrobot actuated by smart materials

Many microorganisms use their tails or appendages for propulsion like in Human and mouse sperms where the appendage is a flexible filament undergoing deformations due to the motors distributed along the length of the filament. In this task, we conduct a novel research to design a microrobot inspired by human sperms actuated by smart materials like dielectric elastomer/piezoelectric composite to produce distributed actuation. We study modelling of swimming microrobot actuated by smart material using fractional calculus tools. The fractional order modelling will be used since this robot is actuated by smart materials and interacting with fluid (considered as viscous damper). Both smart material actuation and viscous dampers are proven to be modelled by fractional dynamics. In addition, a proper fractional/integer order controller will be applied to create non-reciprocal motion for propulsion in low Reynold fluid.

- Task 4.7 Modelling behaviour of biological neurons with fractional-order differential equations

In recent studies, it has been claimed that the dynamic behaviour of neurons can be more appropriately modelled with a non-ideal capacitor and/or inductor, in which voltage-current relationship is given by a fractional-order derivative. In this task, fractional-order neuron model will be studied and new models will be proposed. Circuit implementation of the models will be constructed to observe different behaviours (spiking, bursting, etc.) of the biological neurons experimentally. Synchronization between these neuron models will be also investigated. A detailed bifurcation analysis will be performed and it will be examined whether these models exhibit chaotic behaviour under the certain conditions.

- Task 4.8 Fractional control of industrial systems

The task is devoted to research and implementation of fractional control loops (e.g., FOPID control loops) for particular industrial control problems. Specifically, district heating plants are of interest. Applied fractional-order controllers should work in a multi-loop configuration (MIMO control). Study of automatic tuning possibilities for such control loops must also be carried out.

The deliverables of WG4 can be summarized as follows:

No.	Title	Description	M.

D4.1	Preliminary models	Development of preliminary models for automotive injection systems and of physical and mathematical knowledge on models of Havriliak	10
D4.2	Y1 WS proceedings	Contribution by WG4 to the proceedings of Year 1 WS	12
D4.3	Simulation environment	Detailed models and virtual prototypes; low-order models for FO controllers, development of simulation tools for systems of Havriliak-Negami type	22
D4.4	Y2 WS proceedings	Contribution by WG4 to the proceedings of Year 2 WS	24
D4.5	Control strategies	Advanced FO control algorithms and realization techniques for automotive applications; model of pain pathways and corresponding software	34
D4.6	Y3 WS proceedings	Contribution by WG4 to the proceedings of Year 3 WS	36
D4.7	Final report	Modelling and control of injection systems; Schemes for analysing propagation of electro-magnetic fields in biological tissues; Report on correlation analysis and corresponding software	46
D4.8	Y4 WS proceedings	Contribution by WG4 to the proceedings of Year 4 WS	48
D4.9	Action book input	Contribution by WG4 to the final Action book	48

Based on the activities and deliverables of each WG, the following Milestones of Action can be presented:

Milestone	Description	M.
MS1	Action start: Kick-off meeting and election of WG Chair and Vice-Chair	0
MS2	Year 1 Workshop	12
MS3	Year 2 Workshop	24
MS4	Year 3 Workshop	36
MS5	Year 4 Workshop	48
MS6	Action book	48

3.1.2. GANTT Diagram

In Fig. 1, the GANTT diagram including Action activities, meetings, deliverables and milestones in shown. The Action begins with the Kick-off meeting of MCs, which is followed by other meetings every four months, where management and technical issues will be discussed. If required, additional technical and CG meetings as videoconferences might be scheduled.

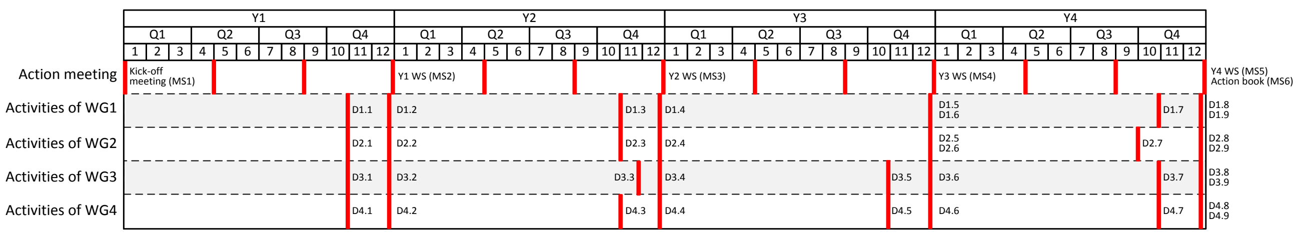

Fig. 1 GANTT diagram of the FRACTAL Action

3.1.3. Risk and Contingency Plans

In the Action, risks that are divided into management and technical/scientific risks can be identified. The levels of Probability and Impact are identified as Low, Medium, High, and Extreme.

Management risks
Risk: Lack of involvement by a WG Chair/Vice-chair
Probability: Low - the researchers supporting already the Action proposal are highly motivated. The WG Chair and Vice-chairs are expected to be mainly selected from already involved researchers that ensure their involvement in accomplish of the Action goals.
Impact: Medium
Prevention/Contingency plan: According to COST rules, the management entities represented by MC Chair, MC and CG, further described in Section 3.2, regularly monitor the activities in each WG. In case this issue arises, they address it by trying to solve the problem with the corresponding WG Chair. If this is proven impossible, MC Chair, MC and CG nominate a new WG Chair/Vice- chair.
Risk: Insufficient interaction within a WG
Probability: Low - the significant dimension of the group of researchers and institutions already supporting the Action proposal ensures that each of the research topics is covered by several researchers within the scope of the Action.
Impact: High
Prevention/Contingency plan: MC, MC Chair and CG monitor the progress in each WG through the periodic reports presented by WG Chairs at MC meetings, and react to any delay by using the tools made available by COST, e.g. reserving more STSMs to a WG that shows lack of interaction. Risk: Insufficient / unsuccessful dissemination efforts
Probability: Low - researchers in the Action have outstanding publishing track records and their academic collaborations ensure efficient spreading of scientific results.
Impact: Medium
Prevention/Contingency plan: Dissemination efforts will be coordinated and monitored throughout the Action by the Dissemination Board (DB), which prepares a detailed dissemination plan and ensures that it is properly followed throughout the Action lifetime.

Technical/scientific risks
Risk: High complexity of the project aims
Probability: Medium - this risk might be caused by the unexpected problems while solving the research activities.
Impact: High
Prevention/Contingency plan: To preclude or solve this risk during the Action duration period, proper cooperation of the research team members and continuous evaluation of the reached results is necessary to be able to deal immediately with this possible risk.
Risk: Changes in the project team members
Probability: Medium - since the project period is 4 years, it is possible that some of the research team members stop their activities within the Action.
Impact: Low
Prevention/Contingency plan: It is expected that each of current proposers is also a tutor of junior researchers eager for the activities solved within FRACTAL. These junior researchers can then be active in the Action and continue in fulfilling the tasks started by their tutors.
Risk: Insufficient financial support of members on national level
Probability: Medium - to be able to proceed with research activities on national level, MCs must submit a project proposal to follow the FRACTAL aims. As the budget for national projects is generally limited, some project proposals can be rejected.
Impact: Extreme
Prevention/Contingency plan: To minimize the risk, the members within each WG, who contribute to accomplish the aims of certain WG and of the Action, will be from different countries. Furthermore,

COST Association
Avenue Louise 149 | 1050 Brussels, Belgium
t: +32 (0)2 533 3800 | f: +32 (0)2 533 3890
office@cost.eu | www.cost.eu
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the research activities of most of MCs are not strictly limited to single WG but can also be active within other WGs, where a lack of the research results will be identified.
Risk: Research results being not up-to-date
Probability: Low – also other research groups around the World are active in the area of fractional order approach. Therefore, it is possible that some of the results of our project will be already known and will not be up-to-date.
Impact: Medium
Prevention/Contingency plan: As the Action is represented by a significant number of well recognized members being active in fractional-order approach, the probability of this risk is low. However, to minimize this risk, also the activities of other research groups not participating in the Action will be observed.

3.2. Management structures and procedures

The Action will be coordinated by the MC, consisting of Chair, Vice-Chair, Secretary, and the MC members from each participating country, nominated according to the COST Guidelines.
WG Chairs and Vice-Chairs will monitor the research activities of the Action for each WG. The MC will be supported by the CG (Core Group), composed of the MC Chair and Vice-Chair, WG Chairs and Vice-Chairs, the STSM manager and Action participants acting as liaisons with other projects or organizations.
In order to guarantee visibility of all activities in the Action, minutes will be timely released by MC Chair and Vice-Chair for MC/CG meetings, and by Chairs and Vice-chairs for WG meetings. In order to optimize interactions between different WGs, the CG will harmonize the meeting plans for the different WGs to minimize the number of trips and allow researchers to participate in more than one WG. Synergies will be sought between Action meetings and events hosted by the organizations with formal liaisons with the Action. Given the key role of dissemination in the success of the Action, a DB (Dissemination Board) in charge of the dissemination plan and of the Action website will be selected within the CG.

3.3. Network as a whole

At the time of the proposal of this Action the network of the FRACTAL included 17 COST Countries and 1 Near Neighbour Country (NNC) with 40 researchers from 28 institutions. That represents a wide international interest in the issues dealt by FRACTAL. The proposers were selected to guarantee a long-lasting impact on not only European research on fractional systems and their utilization in new and up-to-date systems and environments. The proposers have authored a significant number of books, journal and conference papers that due to the anonymity eligibility criterion cannot be presented here. The proposers are in close cooperation with industry partners. Using these relations, the impact of FRACTAL not only to academic area will be guaranteed. Partners from NNCs will support the Action by providing valuable scientific contributions and being active in dissemination of the Action results within their countries.

COST Association
Avenue Louise 149 | 1050 Brussels, Belgium
t: +32 (0)2 533 3800 | f: +32 (0)2 533 3890
office@cost.eu | www.cost.eu