Non-Linear & Complex Systems Group

The Northern Research Partnership: overview: The University of Aberdeen, the University of Dundee and the Robert Gordon University have joined together to establish a research partnership in engineering and related disciplines, known as the Northern Research Partnership.

The purpose of this partnership is to pool research strength in areas common to partner universities, and to exploit areas of complementarity. It is the first time that the institutions have agreed to go beyond collaboration on an ad-hoc basis towards a convergence of research priorities in the area of engineering research. This will enhance research performance of the participating groups in all partner universities by creating critical mass, and increase significantly the competitiveness of research groups in the region. The proposal mirrors the establishment of similar regional partnerships in Edinburgh and Glasgow.

Research activity is taken forward through four JRIs and one overarching joint research group:

JRI for Civil Engineering (also to form part of the national Telford Institute)[1]
JRI for Computational Systems
JRI for Energy & Clean Technologies
JRI for Medical Technologies
Non-linear and Complex Systems Group

The partner universities have also set up a common Graduate School to support and enhance research student activities.

The partner universities have selected members for the JRIs with a view to international excellence, applying stringent criteria relating to research grants and contracts income and RAE submissible publications. The partnership represents a cluster of research groups in the engineering area, comprising 135 researchers, 160 research assistants and 286 PhD students.

Non-Linear & Complex Systems Group: Summary

We propose to establish an internationally leading research group in the area of nonlinear and complex systems and their engineering applications by integrating three interwoven themes of *theory of dynamical systems*, *numerical modelling and analysis*, and *engineering and technology applications*. This initiative, building on the existing strengths at each of the universities, will create a natural environment for multi- and inter-disciplinary research among the research staff from Aberdeen University and Dundee University, providing fundamental research into nonlinear and complex systems that will have direct implications to each of the four Joint Research Institutes.

The Group will produce new and technologically useful results, achieved by (i) applying existing theoretical results from nonlinear and complex dynamics to emerging technology

1 This JRI will also involve a researcher from the University of Abertay, Dundee.

through the four Joint Research Partnerships, (ii) conducting experimental programmes aimed to investigate nonlinear and complex behaviour of engineering and technological systems, and (iii) developing new theories, techniques and tools to facilitate (i) and (ii).

Background

Even relatively simple deterministic nonlinear systems can behave in an apparently unpredictable and erratic manner. When looking at the evolution of their dynamic responses, one often has the feeling that a statistical, rather than a purely deterministic description is more appropriate. This type of behaviour is the attribute of chaotic systems. However, it is well known that chaotic systems can also exhibit an orderly behaviour, and this brings up the term of complexity. Complex systems are understood as the ones exhibiting complicated and intricate features having both elements of order and randomness.

Nonlinear and complex dynamics has been enjoying a vast development for nearly three decades resulting in a range of well-established theory, with the potential to significantly enhance performance, effectiveness, reliability, and safety of physical and biological systems. It is believed that fundamental understanding of various nonlinear phenomena has reached a critical mass and that now is the time to develop technologies which could take advantage of the natural richness (or complexity) of behaviour offered by nonlinear systems, or by a product of nonlinear interactions. A vivid example comes from the control of dynamical systems, where the OGY[1,2] method developed in 1990s allows easy control even of chaotic responses. Moreover, a practical implementation of this method is inexpensive as it uses knowledge about the system dynamics, from which unknown system properties are reconstructed.

The basic philosophy behind our approach is to create conditions that naturally optimise the behaviour of systems and/or processes in such a way that nonlinear interactions will generate favourable operation. The nonlinearities may arise either as inherent characteristics of the natural system/process, or in the interaction of systems that may be artificially created, for example, in a control system. This approach should radically influence the current design, control, and exploitation paradigms in a wide variety of contexts, which because of their incremental nature are often only able to produce marginal improvements in performance of engineering systems.

Examples of areas where the theoretical framework of nonlinear and complex systems has been applied or has had an impact on the scientific and technological outlook include solid and fluid mechanics, manufacturing, control systems, image reconstruction, weather forecasting, climatic changes, dynamics of the solar system, complex networks in biology, medical technology, the cardio-vascular system, neural-brain dynamics, epidemiology, laser systems, plasma waves, the financial markets, and systems biology. The common element in all of the above topics is that they all involve nonlinearity or nonlinear interactions. Since nonlinearities are an inherent and important feature in most physical and biological systems, a thorough understanding of their implications on dynamics is essential. Given a wide spectrum of applications where nonlinearities are important, it is natural that researchers in a broad range of fields have become interested in, and have contributed to, recent developments. Indeed, interdisciplinary developments have in part been responsible for the excitement of the field, as well as its recent extraordinary pace of progress. These interdisciplinary interactions need to be continued and fostered, perhaps in a more structured and focused way, which is the aim of this research group. In particular, it will be feeding fundamental research to generate novel applications within the remit of the four Joint Research Institutes in engineering (Telford), Energy and Clean Technologies, Computational Intelligence, and Medical Technologies. In particular, it is critical that dynamicists (UoA), numerical analysts (UoD), technologists (UoA and UoD) and engineers (UoA and UoD) have close synergetic interactions.

Aim, Goal & Strategy

This joint research initiative is to create and establish an internationally leading research group in the area of systems modelling and analysis to provide novel numerical methods and techniques for applications in the remaining Joint Research Institutes. This will provide natural conditions for inter- and multi-disciplinary research, and it has capability to deliver scientific and technological breakthroughs across the broad engineering and technology spectrum. It will be the strongest in Scotland and one of the top in UK due to its multi-disciplinary nature, and competing effectively with similar groups from Warwick and Bristol. The Group will benefit from well established collaborative research links with the leading international scientists and groups, in particular, H. Kantz (Max-Planck-Institute for the Physics of Complex Systems), W. Ditto (University of Florida), Y.-C. Lai (Arizona State University), G. Rega (University of Rome 'La Sapienza'), T. Tel (Eotvos University), J. Kurths (Potsdam University), R. Stoop (ETH/Zurich), K. Zyczkowski (Jaggielonian University), F. T. Arecchi (Istituto Nazionale di Ottica Applicata), E. Schoell (TU Berlin), Z. Toroczkai (Los Alamos National Labolatory), R. Koberle (University of Sao Paulo), and T. Kalmar-Naggy (Texas A&M).

The main goal of the Group is to produce new and technologically useful results, and this will be attained by addressing the following points: (i) applications of economically viable existing theoretical results from the nonlinear and complex dynamics, (ii) conducting focused experimental programmes aimed to investigate nonlinear and complex behaviour of engineering and medical technology applications, and (iii) developing new theories, techniques and tools to facilitate (i) and (ii).

The strategic case is based on the combined potential of a critical mass of high-quality researchers, strong links with the industrial and commercial sector, an incredible pace of development of the area of nonlinear and complex systems, and broad and enormous application market for the fundamental and applied findings. The opportunity would arise to build a centre of excellence which would attract world class researchers to North East Scotland to compete for research funding with other major centres in the UK and further afield. A by-product could be the establishment of taught post-graduate programmes which would bring high quality post graduate students to the North East, thus establishing a strong national manpower base for future advances and applications across all themes of the Northern Research Partnership.

Novelty and Research Challenges

The novelty comes from a global and generic approach to real systems, which takes advantage of natural or designed nonlinearities to enhance their performances. The major excitement comes from a unique opportunity to form a consortium covering a large number of areas and applications, which are united in its aim to produce a unified framework for exploiting nonlinearities and nonlinear interactions. The following list is by no means exhaustive, but it gives an indication of the applications which can be tackled using a common approach: actuators, biomedical materials, condition monitoring, control, complex communication networks, design methodologies, dynamics of advected particles in flows, manufacturing, mechatronics, magneto-hydrodynamics, MEMS, micro- and nanomechanics, optical solitons, precision engineering, robotics, semiconductors, sensors, signal processing, smart materials and structures, structural health monitoring, ultrafast optics, ultrasonics, wave propagation, and wireless communication. The new systems and processes designed based on the nonlinear interaction principles have the potential of being much more effective, cheaper, compact and environmentally friendly. Although there is a certain awareness of the necessity to include nonlinear behaviour (e.g., nonlinear modules in FEM codes), the general appreciation how much can be gained from nonlinearities and nonlinear interactions is still minimal. Therefore, the main challenge is to change the current technological thinking, which in most cases assumes linear relationships between the components of the system or processes. In addition, there are number of technical challenges, namely:

- To establish a basis for a unified framework harnessing nonlinear and complex systems.
- To classify various nonlinear phenomena systematically and to investigate them with appropriate applications in science, engineering, and medical technology.
- To investigate how various nonlinearities can be introduced to engineering and medical technological systems and processes to produce rich and novel responses.
- To synthesise the obtained results and methodologies into unified strategies, criteria and procedures for design of new devices, sensors and machines for control, manufacturing, remote sensing, and processes and exploitation of natural resources.

A more fundamental and essential challenge will be the development of new basic theory applicable to other fields, a challenge that will be vigorously pursued by the Group. In the initial start-up phase of the Group, areas of research under the category of *development of theories, techniques and tools* will include, but not be limited to active chaotic flows, systems biology, bifurcations in non-smooth systems, classical and quantum scattering, complex networks, dynamics of complexity, non-hyperbolic dynamics, nonlinear data-base modelling, nonlinear programming, numerical methods for ODEs and PDEs, shadowing and numerical modelling, spatially extended systems, and stochastic systems.

References

1. Ott, E., **Grebogi, C.** and Yorke, J.A. (1990) Controlling chaos. *Phys. Rev. Lett.* **64**(11), 1196-199. [1864 ISI cites]
2. Shinbrot, T., **Grebogi, C.**, Ott, E. and Yorke, J.A (1993) Using small perturbations to control chaos. *Nature* **363**(6428), 411-417. [413 ISI cites]