Action plan

Centre for Nonlinear Studies – CENS

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The contributing research teams

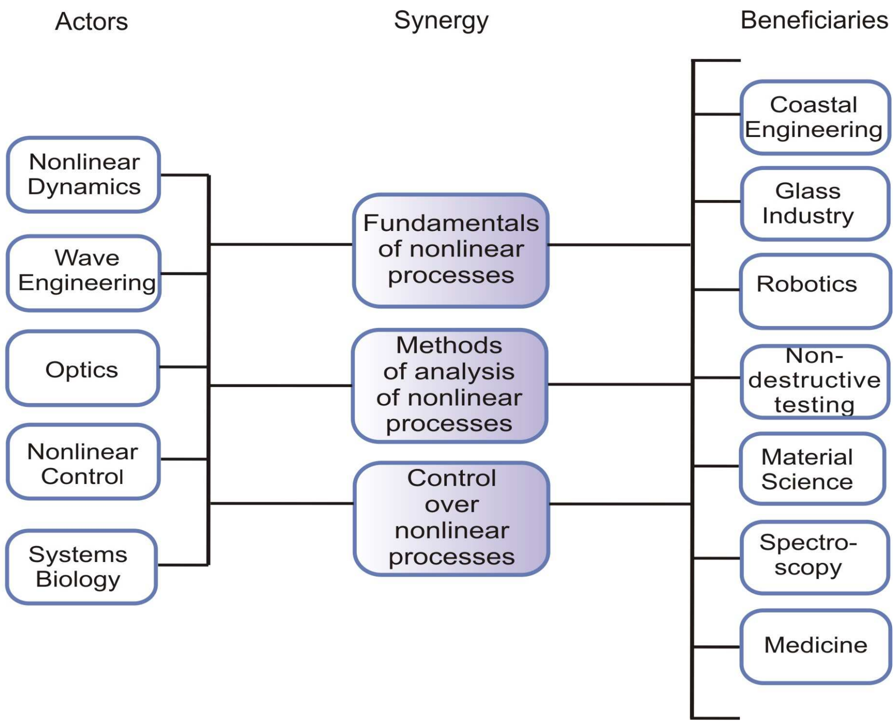
The constituents of our world inherently interact with each other and their environment in a nonlinear way resulting in phenomena, which cannot be predicted by simple linear approaches and theories. Although nonlinear studies originated in mathematics and physics, they are in general intrinsically multidisciplinary. Nonlinear processes are dominating in areas such as chemistry, medicine and physiology, and also computer sciences. More recently this list has been extended to economic and social sciences, and decision support and control systems.

Interactions of inherent nonlinearities and of the components of a whole (which differ widely in character, size and scale) give rise to new effects such as self-organization and the emergence of coherent structures over many scales. This challenges us to combine studies in the analysis, synthesis and control of nonlinear systems to spearhead major developments in contemporary science and meet the needs of society. Our goal is to carry out theoretical and experimental research in the analysis and control of nonlinear processes in a selection of natural and man-made physical and biological systems.

CENS was originally founded in 1994 as a cluster-type research unit to concentrate the national research efforts within nonlinear dynamics and related areas, and was an Estonian Centre of Excellence in Research in 2002-2007. Now the composition of the new CENS reflects both past successes and new challenges. Out of the original **Nonlinear Dynamics** (ND) group two teams have grown and become independently funded units: **Wave Engineering** (WE) and **Systems Biology** (SB). Two other groups have been invited to join to increase the scope and the potential for synergy: the **Optics** (OG) group and the **Nonlinear Control Systems** (NC) group. Four groups are part of the Institute of Cybernetics at Tallinn University of Technology; the Optics Group belongs to the Institute of Physics at the University of Tartu. Activities of Groups and possible beneficiaries are shown in Fig 1.

Fig. 1

Activities of CENS:



The **Nonlinear Dynamics** group holds key competence in (i) wave motion in solids, (ii) soft matter physics, and (iii) photoelasticity.

The studies in (i) focus on nonlinear deformation waves in micro-structured solids, which are of growing importance in contemporary technology (functionally graded materials, metal-ceramic composites, etc.). The team has internationally recognized competence in mathematical modelling [ND1][1] of wave motion, in the analysis of dispersive and nonlinear effects including emerging solitary waves, and in solving the inverse problems [ND2] of material characterization. The novel concept of internal variables [ND3] introduced by the group permits to unify the theoretical background in modelling. Based on these important results, the main goal is now to develop hierarchical multi-scale modelling of nonlinear wave motion in micro-structured materials relating mesoscopic physics to continuum mechanics. The studies will reflect the existence of possible nonlinearities over the scales, dispersive/dissipative effects and thermodynamical consistency in numerical calculations. The nonlinear effects will be used for new non-destructive testing methods of material characterization based on wave-wave and wave-material interaction. For understanding the behavior of the microstructure, 3D visualization methods and experiments must be developed.

For (ii), our studies deal with nonlinearities in interdisciplinary areas from mechanics to econophysics, which all are characterized by self-organization and power laws [ND4, ND5]. The new challenges include studies of turbulent mixing of passive scalars in oceans and flows of free-slip surfaces of turbulent water (problems of contamination),

[1] References are made to example publications of each group listed at the end of the text. See the attached CVs for the full list of publications of every scientist

droplet nucleation in warm clouds, and financial drawdown, which is analogous to turbulent mixing.

In (iii), the Laboratory of Photoelasticity deals with the analysis of stress fields in glasses [ND6], where the team has even created a spin-off company GlasStress. The goal here is to develop the theory and algorithms of nonlinear photoelastic tomography for non-destructive measurement of 3D stress fields, especially in very thin objects.

The Laboratory of **Wave Engineering** represents deep knowledge in nonlinear wave theory and modelling for fluids, with the focus on applications in the marine and coastal environment.

The team is the worldwide leader of studies into several classes of transient and localized wave phenomena (similar to those studied by OG for light waves, see below) such as soliton interactions, freak waves and vessel wakes in shallow water, and wave run-up [WE1–3]. Although linear ship wakes are well known, the importance of the remote impact of ship traffic due to nonlinear wake waves [WE4] has now been recognised through the analysis of the WE group. The role of nonlinear phenomena in surface wave fields is particularly large in semi-sheltered basins such as the Baltic Sea, where our studies [WE5] form the state-of-the-art of wave climate research. WE is also pioneering in the development towards engineering estimates of the magnitude of marine and wave-induced coastal hazards and creating novel methods for their mitigation [WE6] that have virtually no analogues in the world.

Topics of particular interest are: fundamentals of nonlinear wave phenomena (rogue waves, nonlinear interactions, run-up phenomena, 2D propagation, wave mathematics); properties and spatio-temporal variations of wave fields (wind waves, long-wave phenomena, ship waves, internal waves); applications for coastal engineering and coastal zone management (quantification of marine-induced hazards and wave loads, wave energy issues, preventive methods for environmental protection, etc.)

The Laboratory of **Systems Biology** has leading expertise in the analysis of the regulation of intracellular processes.

By experimental and theoretical analysis of highly non-linear phenomena, such as biological processes, SB members contributed to the understanding of the regulation of heart physiology on molecular [SB1], cellular [SB2, SB3], tissue [SB4], and organ level. We have developed new approaches to quantitatively analyze the morphology of live cells [SB5] as well as participate actively in the enhancement of mathematical analysis of microscope images [SB6]. The SB work has been recognized by a Wellcome Trust International Senior Research Fellowship, one of the most prestigious fellowships in the biological and medical sciences.

The main SB aim is to study the regulation of intracellular processes and understand the functional influences of highly nonlinear intracellular interactions. The focus is on energy transfer regulation and analysis of intracellular diffusion in heart muscle cells. In addition, we look on the development aspect of intracellular interactions (trout *vs* rat) and use genetically modified mice for perturbation of intracellular control. Future activities – using a combination of experimental (following ethical conditions) and theoretical methods – concern: analysis of diffusion of molecules in the crowded intracellular environment of heart muscle cells; mathematical modeling of energy transfer networks in the heart muscle; energy consumption and regulation of energy transfer at different mechanical load protocols; the role of the Na+/Ca2+-exchanger in excitation-contraction coupling and energetics; interdependence of reactive oxygen species and Ca-signaling in initial stages of heart failure; molecular interaction between creatine kinase and adenine nucleotide translocase.

Areas of key expertise of the **Optics** group within the scope of CENS are ultrafast optics, optical and nonlinear spectroscopy, and especially the so-called localized waves (LW).

A breakthrough in the study and applications of electromagnetic and acoustic LWs occurred in the end of the 1990s, when OG introduced methods of physical and ultrafast optics into the subject (two pioneering papers [OG1, OG2] have received more than 270 citations). The study of LWs has expanded rapidly – a number of new teams have entered the field worldwide and new types of practically promising LWs have been discovered, e. g., nonlinear propagation of Bessel-type LWs and the so-called Airy beams and bullets have become a hot topic in Nature, Nature Photonics and other top-impact-factor journals.

Collaboration between OG and Georgia Tech researchers has recently resulted in a series of pioneering results (work summarized in [OG3] was selected by the worldwide magazine Optics & Photonics News into a set of 28 of "the most exciting peer-reviewed optics research to have emerged over the past 12 months."). The OG group also contributes to applying the Bessel-, Mathieu-, etc., conical beams/LWs in nonlinear spectroscopy [OG4] and addresses the problems of nonadiabaticity, quantum-mechanical inverse problems and solving the Schrödinger equation [OG6] that also describes deep-water waves, linking it to WE.

The **Nonlinear Control Systems** group holds unique competence in dynamical control systems on time scales [NC1, NC2, NC3].

This is an emerging area of research to model dynamics of interspersed continuous and discrete evolution periods that frequently and inherently occur in nonlinear environments (e.g. propagation of cracks or shock waves). The NC group also incorporates competence in robust control [NC4] and in synthesis methods of reactive planning algorithms that are highly efficient in on-line testing and autonomous robot action planning applications [NC5].

The NC group will focus on novel methods and tools for solving fundamental/generic problems for nonlinear control systems towards the unification of discrete- and continuous-time control systems. The aim is to integrate our research with progress in non-traditional application areas of control theory such as biology, environmental science and material science. Three formalisms (time scale calculus, pseudo-linear algebra and associated algebraic computation methods, and algebra of functions) complement each other to reduce the programming effort in symbolic software implementations. The algebra of functions allows the development of novel solutions for discrete event systems used in modern computer-based control. The time scale tools will be systematically applied to the analysis of hierarchical multi-scale control systems (that may be discrete or continuous at different levels and/or time models) using the recently introduced idea (Willems, 2007) that systems are interconnected by sharing variables, with the behavioral approach as the supporting mathematical language. This systematic, modular and hierarchical methodology is easy to adapt to computer assisted modelling.

Synergy and added value

The key asset that makes synergy feasible is that all proposed studies are characterized by the decisive role of a few universal nonlinear phenomena (such as essential interaction between the constituents in a wide range of scales in space and time, emerging features and hierarchies, irreversibility, nonlinear feedback, etc.) that are intrinsic to all the seemingly different environments and that require multilevel control approaches over space and time scales. For example, equations and dynamics of rogue waves in marine (WE) and optical applications (OG) are equivalent (Solli et al. 2007); also solitons and their interactions in radically different environments are mathematically equivalent [WE1].

This universality makes it possible to immediately employ improved theoretical understanding and increased new research/experimental data in one field for progress in other areas. For example, continuum theory (ND) is the basis for dynamics of solids, fluids (incl. water waves, WE) and optics (OG). Nonlinear PDEs and difference equations are basic models for all the groups; and all will benefit from progress achieved in either analytical or numerical methods for any particular problem. Synergy is obtained by using unified approaches: control over the steering of solitons; control over the contraction of a single heart muscle cell; optical wavebeams and photoelasticity; long waves in solids and fluids; fractality in biophysics, mechanics, econophysics; internal variables from continuum theory to biophysics; similarity of modelling (Schrödinger equation) in optics and sea waves, etc. A summary of added values through synergy is depicted in Fig 2.

Fig. 2
Synergy:

Added value given / Added value obtained	Nonlinear Dynamics	Wave Engineering	Optics	Nonlinear Control	Systems Biology
Nonlinear Dynamics		methods, 2D soliton theory	optical wavebeams	control over steering solitons	internal variables in biophysics
Wave Engineering	methods, turbulent mixing, 3D images		models of dispersive waves	control over long waves	
Optics	solitons, laser-based tomography	solitons, wave packets		growth of nanotubes, control of loca-lised waves	spectro-scopy
Nonlinear Control	control over wave processes	control in environ-mental processes	control over wave processes		control in real time of single cell
Systems Biology	thermo-dynamics in physiology, 3D images		optical microscopy	control of cell energetics	

Consequently, the central aim is to further develop existing synergies between groups stemming from the original CENS (ND, WE, SB) and create new ones by involving additional groups that fit the general philosophy of nonlinearity (OG, NC), addressing together similar problems in different media, at different scales and in different contexts. To act as catalysts, regular interdisciplinary seminars and workshops will be held to initiate and develop joint research, which is of course the ultimate measure for creating added value beyond just the sum of individual efforts. Sharing of unique equipment belonging to the individual teams (computer cluster, sea wave measurement systems, optical devices, etc.) is foreseen as well.

Expected results

The planned research is intrinsically *interdisciplinary* and *cross-disciplinary*, and is positioned at the intersection of several disciplines in contemporary research into mechanics, Earth sciences, coastal engineering and management, and control of complex systems and biosystems. The unifying tool is the theory of nonlinear wave equations (for propagation of energy through the medium) and complementary constitutive equations (describing changes to the properties of the medium).

The strategic aim is a unified framework for the analysis, synthesis and control of the mechanisms responsible for wave-driven impact in different media and on different scales, from large-scale coastal disasters to strongly nonlinear effects and feedbacks on engineering and cell energetics scales down to small-scale wave-driven processes in optical applications. We are going to systematically exploit that the scale-similarity and mathematical equivalence of different wave-driven phenomena in radically different media makes it possible to perform research for one specific safe and well-controlled situation, and then generalize the results to drastically different scales of forces, impacts and levels of danger: e.g., from tides and tsunamis down to local wind waves; from optical rogue waves up to monster waves in the deep ocean.

ND: New results are expected in explaining the hierarchical behavior of micro-structured solids and in solving the corresponding inverse problems. Theory and methods will be developed for nonlinear photo-elastic tomography as well as for turbulent mixing and transport.

WE: The focus will be on nonlinear wave dynamics and the impact of waves in the coastal environment (incl. coastal engineering structures), ranging from wave excitation and propagation over the sea surface to wave-coastal zone and wave-structure interaction. The research, formulated in terms of marine and coastal environments, is directed towards a unified framework for the analysis of the mechanisms responsible for wave-driven phenomena in various media governed by equivalent equations such as the KdV or Schrödinger equations.

SB: Research aims to explain regulatory mechanisms of metabolic processes and cell function in the heart. By applying expertise in thermodynamics of internal variables, non-linear dynamics (ND), control principles (NC), the additional knowledge about underlying processes involved in heart energetics and mechanics will be obtained. The results are expected to advance our understanding of such clinically important phenomenon as preconditioning in ischemia-reperfusion damage of the heart.

OG: The aims include both the theoretical and experimental study of new sophisticated and nonlinear generalizations of the LWs and their possible applications. Here the expertise of the other groups in soliton and nonlinear wave modelling, nonlinear dynamics and control is most valuable. The goal of investigations of applying the Bessel-, Mathieu-, etc., conical beams/LWs in nonlinear spectroscopy is to get information about potentially useful nonlinear processes in crystals and fibers and to extend operational characteristics of available laser sources, with obvious applications and joint research in laser-based optical tomography.

NC: The development of generic tools independent of application domains is planned, thus providing the option to use them in a variety of settings. The goal is to integrate the methods of control with the research activities in other disciplines, branching out beyond traditional application areas of control systems, and becoming a contributor to high-risk long-range application areas such as systems biology (SB), environmental science (WE) and materials science (ND).

Societal importance

Within CENS, there is already a track record for timely and effectively reacting to urgent needs of society. For example, in January 2005, the WE work led to a timely warning about a devastating flood approaching Estonia after the failure of the routine warning system to issue a proper forecast [WE7], and in 2009 to the acceptance of a declaration of the Parliament of Estonia (Riigikogu) about major gaps in the analysis of the environmental impact of the Nord Stream pipeline.

In general, the proposed CENS research corresponds to the focal points of the ***Estonian R&D&I Strategy*** *Knowledge-based Estonia* 2007–2013. Our studies are related to high added value in material technology (ND, OG), information technologies (NC) as well as in health care (SB) and environmental protection (WE).

CENS research has a substantial societal dimension for Estonia in several aspects. The effective analysis of various nonlinear problems, solving the associated direct and inverse problems and applying the results to fundamental and engineering sciences (e.g., non-destructive testing based on the analysis of wave shapes, processes in microstructured and laminated materials, etc.) is a cornerstone of industrial progress. Understanding and forecasting wave-induced marine coastal hazards is crucial for a country with a 3800 km long coastline. Heart disease is a serious medical problem in Estonia and the entire world with a large fraction of the population affected by it. Our research into nonlinear mechanisms regulating intracellular processes and into functional influences of intracellular interactions contributes to its mitigation on a global scale. The application of ultrafast optics and the development of a new generation of laser devices not only contribute to science in general but also open the way for the development of high-tech production based on local competence, in this way increasing the competitiveness of Estonian industry.

European dimension

The overall objective of nonlinear studies corresponds to general European trends featured in EU projects such as *Complexity NET*, *Global Systems Dynamics*, *FuturICT* (all with CENS participation). CENS researchers are clearly competitive in the acquisition of international funding through the EU framework programmes, and from other sources such as the Wellcome Trust and the BONUS programme for funding Baltic Sea science. CENS members have been or are coordinators of several larger international projects (STREP Roboswarm, Transfer of Knowledge Project CENS-CMA, BONUS project BalticWay), and the overall international funding for CENS-related research in the last 5 years exceeds 2.3 M€.

Human Capital development

All teams (note that the IoC is not a teaching body while the OG in Tartu has a substantial teaching load starting from 2nd-year students) have substantially contributed to teaching of both undergraduate and graduate students (e.g., 24 PhD and numerous MSc awarded under their supervision since 2000). In addition, 30 post-doc level researchers and 7 PhD students from abroad have been working in the IoC since 2006. CENS also has a significant contribution to gender balance: one team leader, 7 researchers and 10 PhD students are women.The contribution of the CENS members to the development and improvement of the curricula of the relevant fields in TU and TUT [(technical) physics, civil and environmental engineering, etc.), to international PhD studies and hosting post-doctoral research not only widens the scope of higher education in Estonia but clearly increases attractivity of the host universities and contributes towards both their internationalisation and educating the new generation of top-level Uni teachers in Estonia. Last but not least, the CENS cooperation will level off gaps in the existing local infrastructure and will bring the working environment (that does have some shortages to-day) to internationally recognised standards.

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