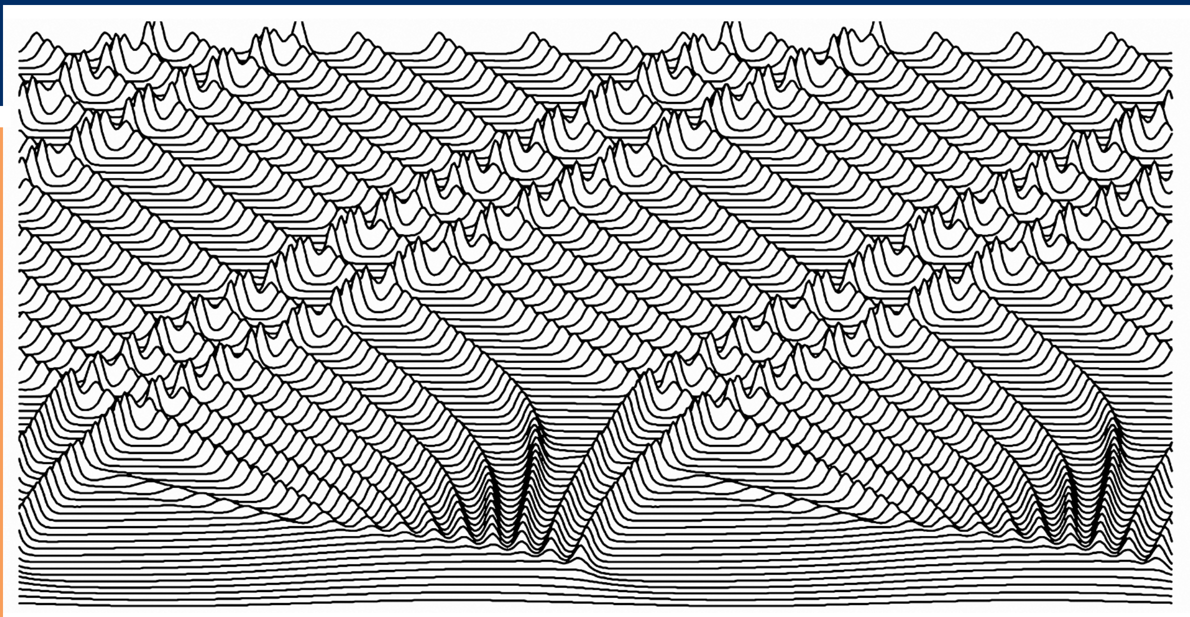
cENTRE FOR NONLINEAR STUDIES



2011 2015

HIGHLIGHTS

Tallinn, Estonia

What is CENS

- CENS stands for Centre for Nonlinear Studies
- CENS is a virtual network of research groups
- CENS idea is to bring under one umbrella the scientific potential of Estonia engaged in interdisciplinary studies of complex dynamical nonlinear processes

What CENS aims at

- to be at the frontier of science
- to create a vibrant research atmosphere
- to react to national interests
- to participate in international research
- to disseminate knowledge

History

1999	CENS was founded
2002-2007	CENS was included into the first Estonian National Programme for Centres of Excellence in Research (supported by the State budget)
2009-2011	CENS was a Centre for Excellence in Research of Tallinn University of Technology
2011-2015	CENS was included into the second Estonian National Programme for Centres of Excellence in Research (supported by the EU through the European Regional Development Fund – project TK 124)

Annual Reports – see http://cens.ioc.ee

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Contents

Aknowledgements

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INSTITUTE OF CYBERNETICS
AT TALLINN UNIVERSITY OF TECHNOLOGY

INSTITUTE OF PHYSICS
UNIVERSITY OF TARTU

Structure of CENS

Four units from the Institute of Cybernetics (IoC) at Tallinn University of Technology (TUT), one unit from University of Tartu (UT):

Head Prof J. Engelbrecht

Nonlinear dynamics (IoC at TUT) – Prof J. Kalda
The group deals with nonlinear wave motion in solids, soft matter physics, and photoelasticity

Wave engineering (IoC at TUT) – Prof T. Soomere
The group studies nonlinear wave motion with the focus on waves on sea and impact of waves in coastal regions

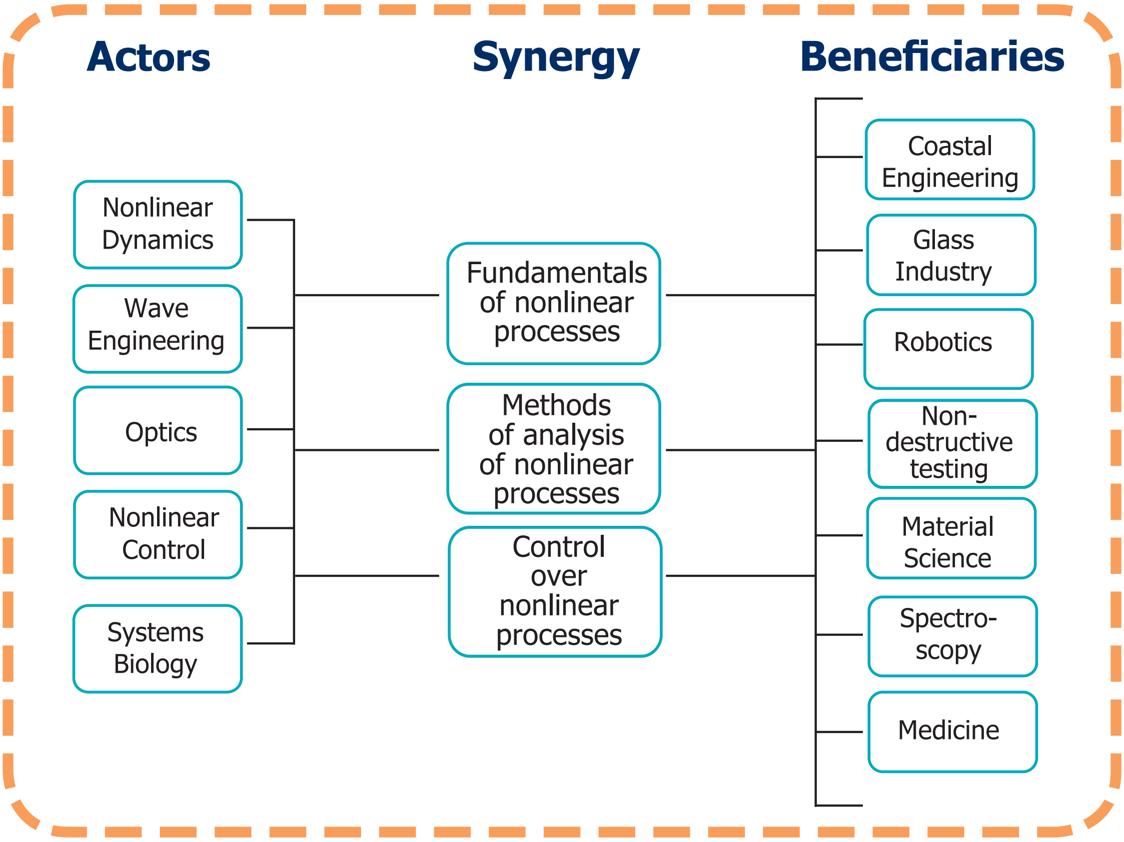
Systems Biology (IoC at TUT) – Dr M. Vendelin
The group is focused on unravelling the intricacies behind regulation of intracellular processes in cardiac muscle cells

Optics (UT) – Prof P. Saari
The group deals with physical and ultrafast optics, particularly in non-diffracting and accelerating localized waves

Nonlinear Control Theory (IoC at TUT) – Dr Ü. Kotta
The group studies dynamical control systems on time scales and unification of discrete- and continuous-time control

The research is intrinsically interdisciplinary and cross-disciplinary and is positioned at the intersection of several disciplines in contemporary research into mechanics, marine sciences, optics and biosystems. 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 paying a special attention to interaction of waves, fields and internal structures. Activities of groups and possible beneficiaries are shown in Figure below.

Activities of CENS



In addition to direct research results, the studies in CENS have a substantial societal dimension in Estonia in several aspects: material technology and nondestructive testing, wave climate on the Baltic Sea and coastal hazards, intracellular processes and heart diseases, optics and laser devices, etc. These studies correspond to the Estonian R&D&I Strategy (2007-2013 and 2014-2020) and to general EU trends. In addition, the human capital development (MSc and PhD studies) and dissemination of knowledge are supported. This Report gives an overview of the best results in CENS over 2011-2015. Annual results and activities are reported in Annual Reports (see http://cens.ioc.ee), a summary of earlier results is given in "CENS Highlights 2003-2007" describing the research within the first Estonian Programme for Centres of Excellence in Research.

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Keywords

GENERAL

COMPLEXITY

INTERDISCIPLINARITY

NONLINEARITY

DYNAMICAL INTERACTIONS

SPECIFIC

SOFT MATTER PHYSICS

MICROSTRUCTURED SOLIDS

SOLITONS

WATER WAVES

SHIP WAKES

EXTREME WAVES

COASTAL ENGINEERING

PHOTOELASTICITY

ACOUSTODIAGNOSTICS

CELL ENERGETICS

DIFFUSION

CONTROL THEORY

WAVE OPTICS

LOCALIZED LIGHT PULSES

RESEARCH RESULTS

NONLINEAR DYNAMICS

MAIN ISSUES

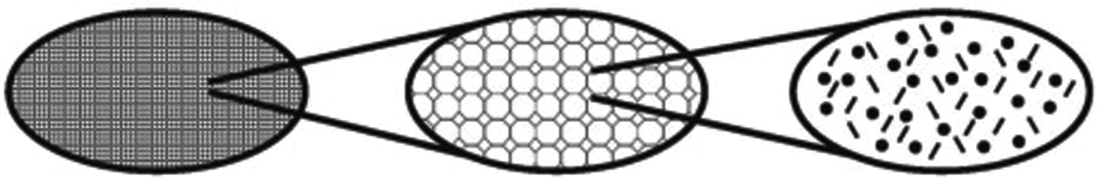
WAVES IN SOLIDS
the concept of dual internal variables is elaborated which forms a physical basis for modelling wave motion in nonlinear microstructured solids; these well-grounded models are used for the analysis of direct and inverse problems;

SOFT MATTER PHYSICS
the mechanisms of turbulent mixing are proposed and the theory of moving fractal sets with corresponding scaling laws is established;

PHOTOELASTICITY
methods of integrated nonlinear photoelastic tomography are elaborated with applications in industry.

THEORY OF CONTINUA AND INTERNAL VARIABLES

The theory of canonical thermomechanics is formulated in terms of dual internal variables. This approach allows describing the internal structure of materials as internal fields. The corresponding mathematical models of wave motion in microstructured solids are derived which take consistently into account nonlinear, dispersive and temperature effects and possible multiscale of a microstructure. For example, a novel mathematical model for waves in thermoelastic microstructured materials is able to account simultaneously for the effects of microdeformation and microtemperature (temperature fluctuations in the microstructure).



Multiscale microstructures

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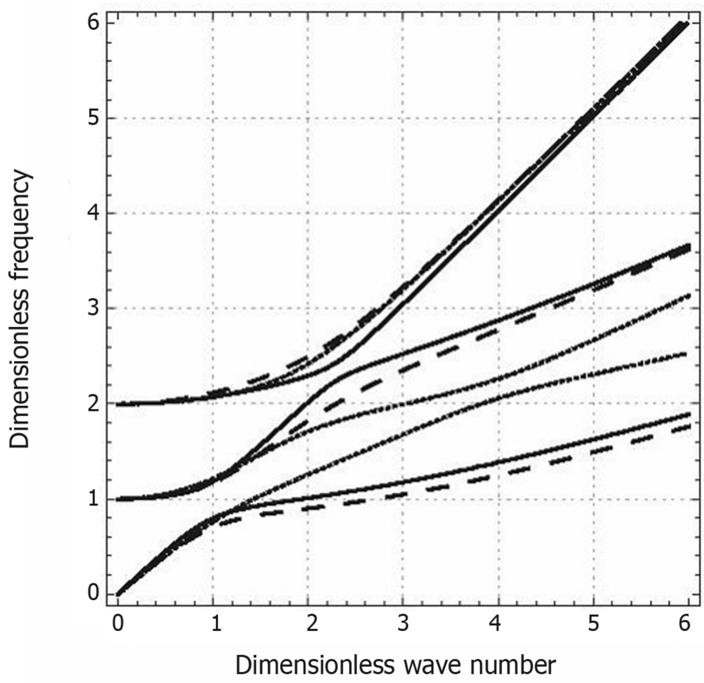
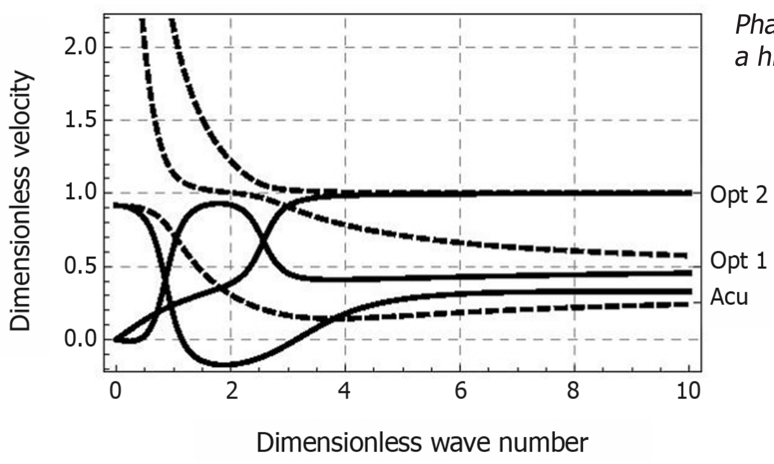
ANALYSIS OF WAVES IN MICROSTRUCTURED SOLIDS

The large-scale analysis of dispersive and nonlinear effects has revealed mechanisms of wave profile distortions, including waves in hierarchical microstructured solids. The accuracy of models is analysed over a large range of material parameters and frequencies of excitations with establishing the novel dimensionless parameters which govern the phase and group velocities. The negative group velocity is proved to exist for a certain multiscale and felt-type materials. Elastic wave propagation through elastic diffraction gratings is studied and the diffraction patterns including a self-imaging Talbot carpet are established.



Dispersion curves for a hierarchical microstructure



Phase and group velocities for a hierarchical microstructure

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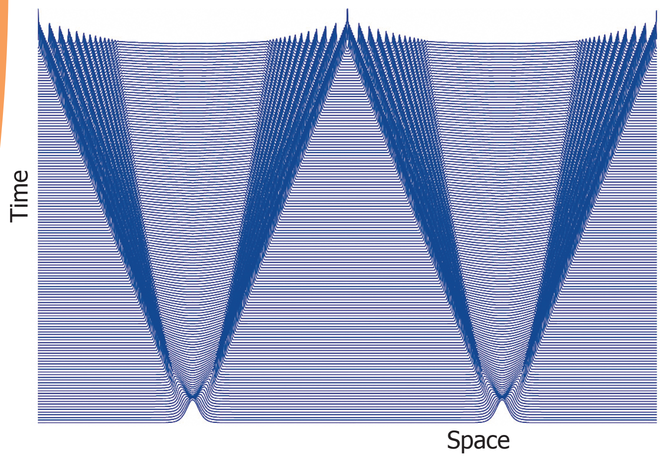
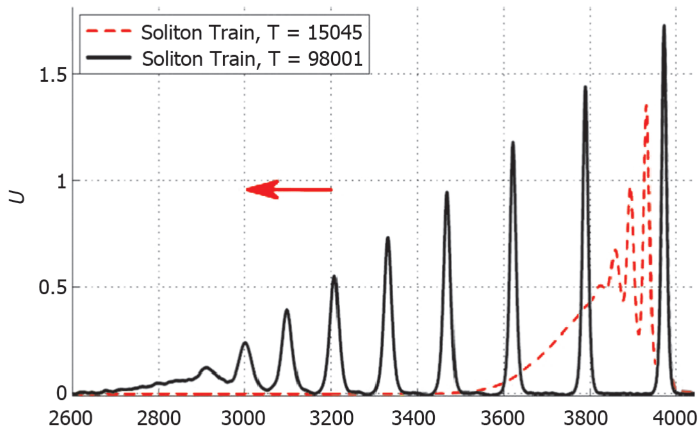
SOLITONS AND SOLITARY WAVES

The mechanisms of emergence of soliton ensembles and solitonic structures are determined for cases with complicated dispersion. The emergence of solitons in Boussinesq-type (two-wave) models and hierarchical KdV-type (one-wave) models which describe waves in microstructured solids is analysed in detail.

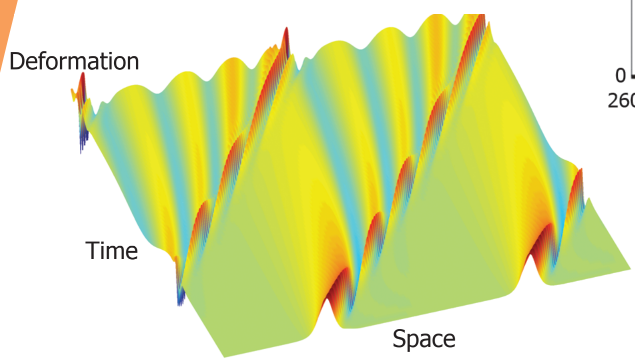
The existence of hidden solitons is demonstrated for a hierarchical KdV system in dependence on the material parameters. A novel nonlinear model with physically consistent dispersion properties is derived for waves in biomembranes. This model is able to describe solitons and soliton trains.



Scheme of Boussinesq soliton trains



Formation of a soliton train in a biomembrane



Plaited solitons

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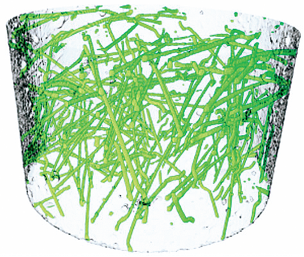
FIBRE-REINFORCED MATERIALS

The theory of short fibre reinforced materials is derived based on using alignment tensors and orientational parameters. The novel methods for measuring the orientation of fibres in short fibre reinforced concrete are proposed and applied. Within these studies a semi-immersive 3D visualization system (Kyb3) has been designed and installed.



Fibre reinforced concrete and the 3D visualization of fibres

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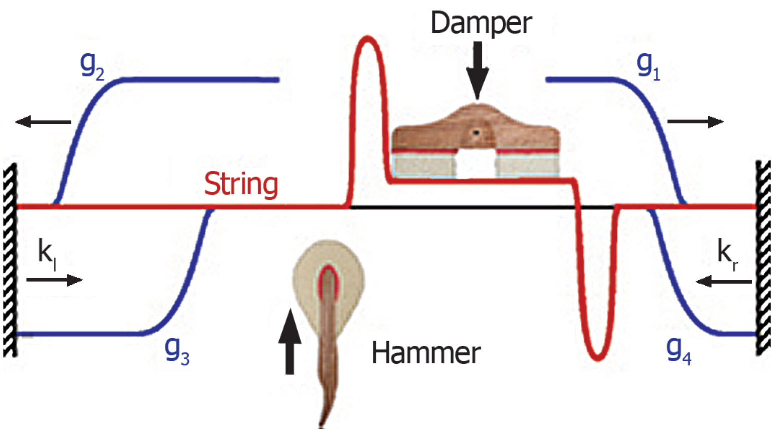
SOUND GENERATION

Studies are focused on sound generation in stringed instruments. A novel governing equation for waves in felt is derived describing impact of piano hammers. String vibrations are analysed analytically and experimentally with attention to boundary conditions (geometry of capo bars).



Waves in a string generated by a piano hammer

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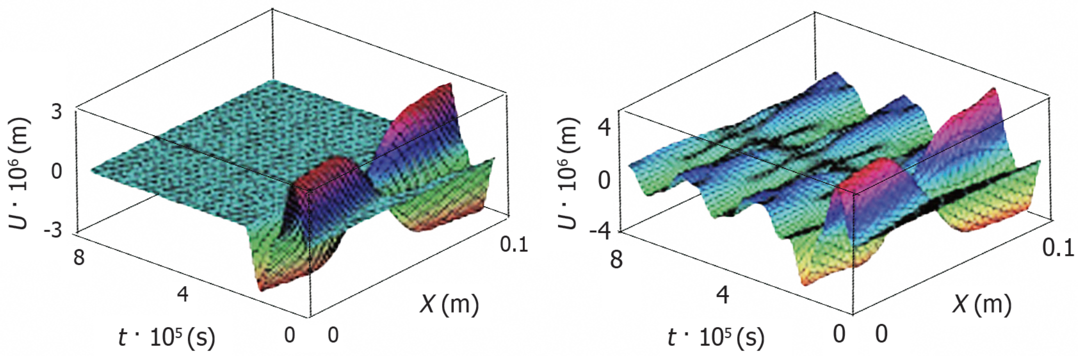
INVERSE PROBLEMS AND ACOUSTODIAGNOSTICS

A novel method for nondestructive testing is proposed on the basis of asymmetric deformation of solitons in microstructured materials. The algorithms based on counterpropagating ultrasonic bursts are derived for solving the inverse problems of functionally graded materials. The accuracy of such algorithms is enhanced by using phase plots and parametric plots. A two-dimensional evolution equation is derived for describing ultrasonic wave beams in microstructured materials.



Interaction of bursts in homogeneous and inhomogeneous materials

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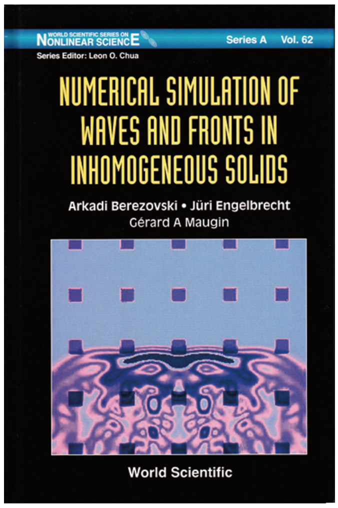
METHODS



The governing equations derived for describing complicated physical effects are, as a rule, not analytically solvable. This is the reason why numerical simulation must be used. Two methods are widely applied with modifications needed for enhancing the accuracy of results.

The thermodynamically consistent finite volume method is derived and applied for wave and front propagation problems. The pseudospectral method with filters is applied for solving the evolution equations including also the mixed derivatives.

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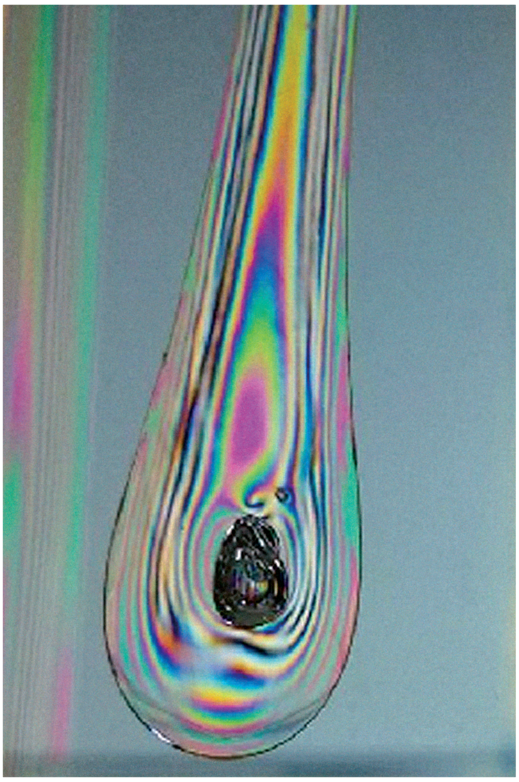
PHOTOELASTICITY

An algorithm of photoelastic tomography for the determination of 3D stress fields is derived and its reliability checked in the axisymmetric case against the measurements of stresses in glass fibres and in stems of wine glasses. For the first time the stresses in a Prince Rupert drop (PRD) have been experimentally determined with integrated photoelasticity.

The photoelastic scattered light polariscope SCALP is designed and applied. Glass quality control equipment is supplied to glass industry through the GlasStress Ltd.

Scattered light polariscope SCALP



Fringe pattern of the Prince Rupert Drop

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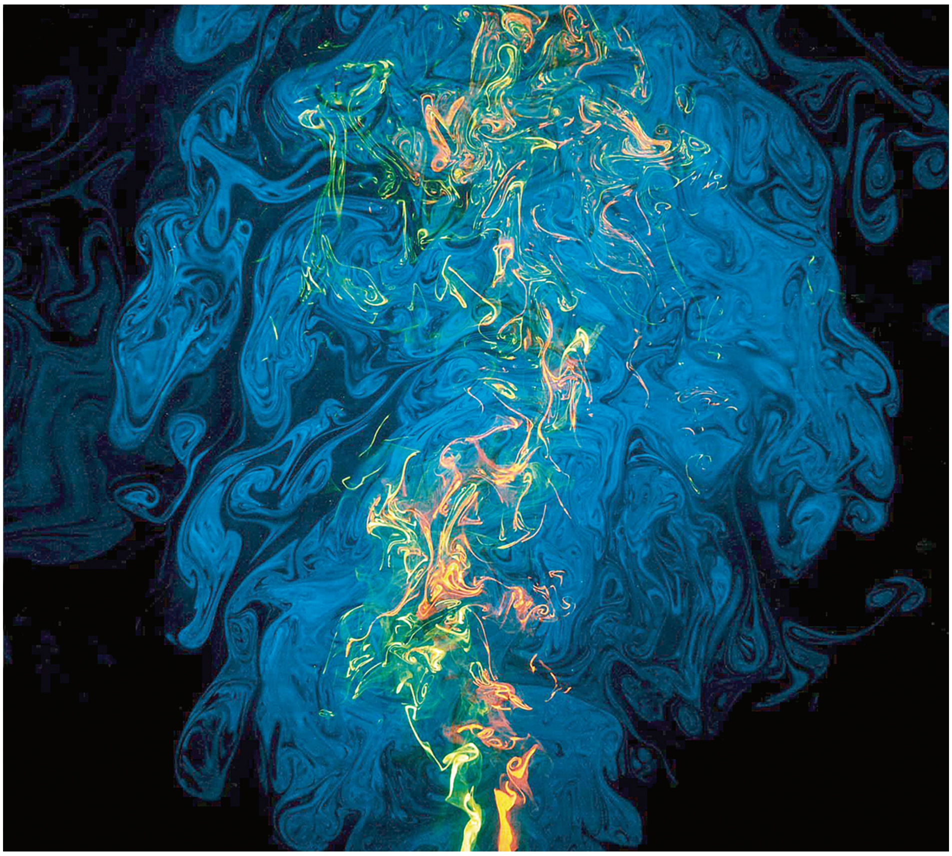
SOFT MATTER PHYSICS, TURBULENT MIXING

The stochastic triplet-map model of turbulent mixing is extended for describing the passive tracers in compressible flows and the patchiness of pollutants on the sea surface; a profound mismatch between experimental results regarding the behaviour of tracers in real time-correlated flows, and the existing theoretical results for tracers in ideal Kraichnan flows has been explained theoretically; a novel device for optimal mixing of two compounds is devised which maximizes homogeneity of mixing.



The mixing of distant sources in a turbulent flow

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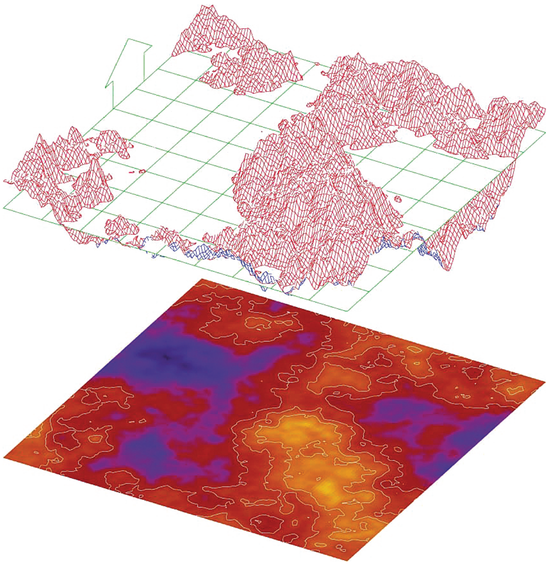
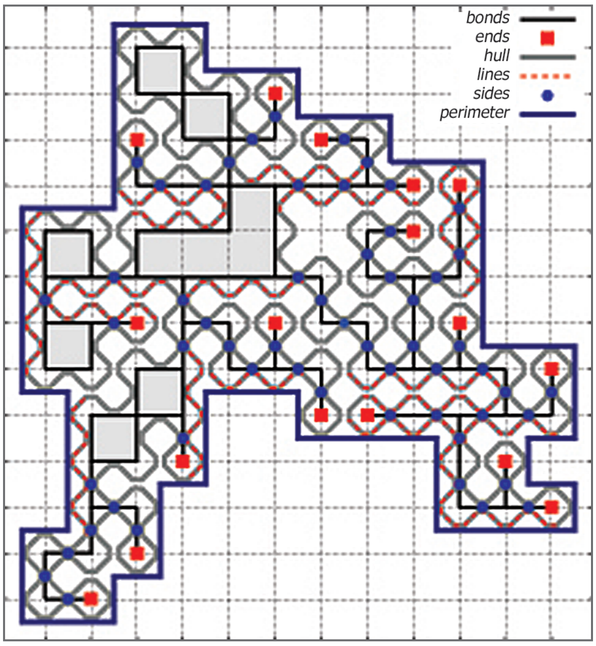
SOFT MATTER PHYSICS, SCALING EXPONENTS AND FRACTALS

A novel method for determining scaling exponents from finite-size Monte-Carlo simulation data has been tested using fractal sets like percolation clusters; a multivariable method for finding scaling exponents is used in the analysis of classical percolation problems; a universal relationship between the scaling exponents has been established describing the time-fluctuations of the intersection size of two moving fractal sets; a scaling law has been derived for the field of binary relations in turbulent flows when reagents are injected from point sources. The mechanism for anomalously fast nucleation of droplets is explained by highly inhomogeneous and intermittent widening of the droplet-size distribution spectra. The mechanism of motion of oriented particles on fractal surfaces is proposed. The models for economic decision making are proposed under conditions of short term noise and long term chaos.



Intersection of two moving fractal sets



General structure of fractal sets for percolation problems

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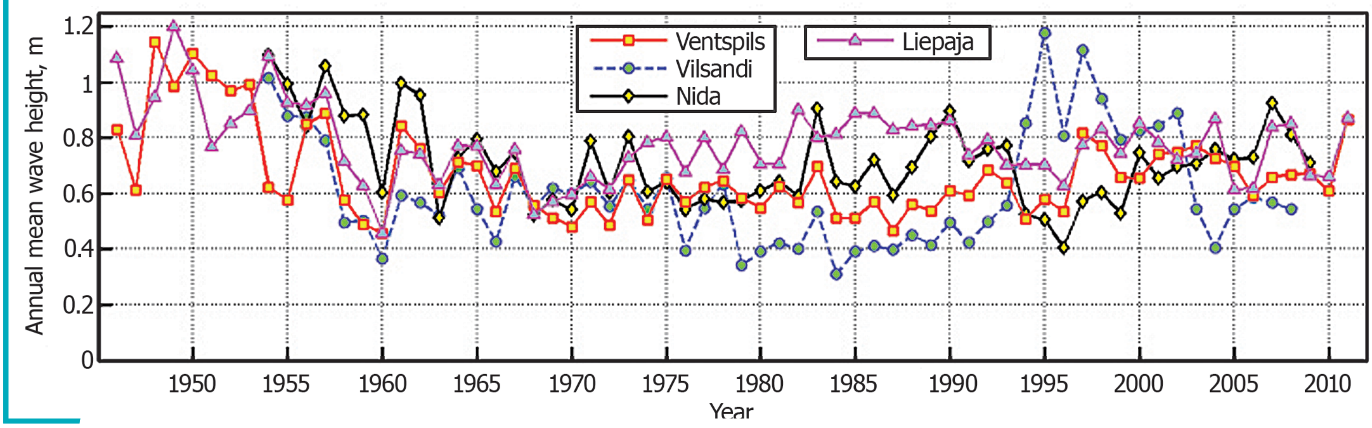
WAVE ENGINEERING

MAIN ISSUES

Attention is focused on the analysis of wave climate and currents in the Baltic Sea which affect pollution and coastal environment; trends are established and proposals made for improving the situation; mechanisms of wave generation on the sea including freak waves/tsunamis and their run-ups to coast are established which permit to find ways for better coastal management.

WAVE CLIMATOLOGY

Spatial patterns of variations in the Baltic Sea wave properties are described. The basic features of the wave climate in the South-Western Baltic Sea are established based on the second longest instrumentally recorded wave time series in the Baltic Sea at the Darss Sill in 1991-2010. The wave energy resource theoretically and practically available in a semi-sheltered shelf sea of moderate depth and with highly intermittent wave climate has been quantified on the example of the Baltic Sea. Wind wave climatology in the eastern part of the Baltic Sea has been extended back to 1946 and the first approximation of a similar climatology for Lake Peipsi has been constructed.



Annual mean wave height at four observation sites on the eastern Baltic Sea coast (1946-2011)

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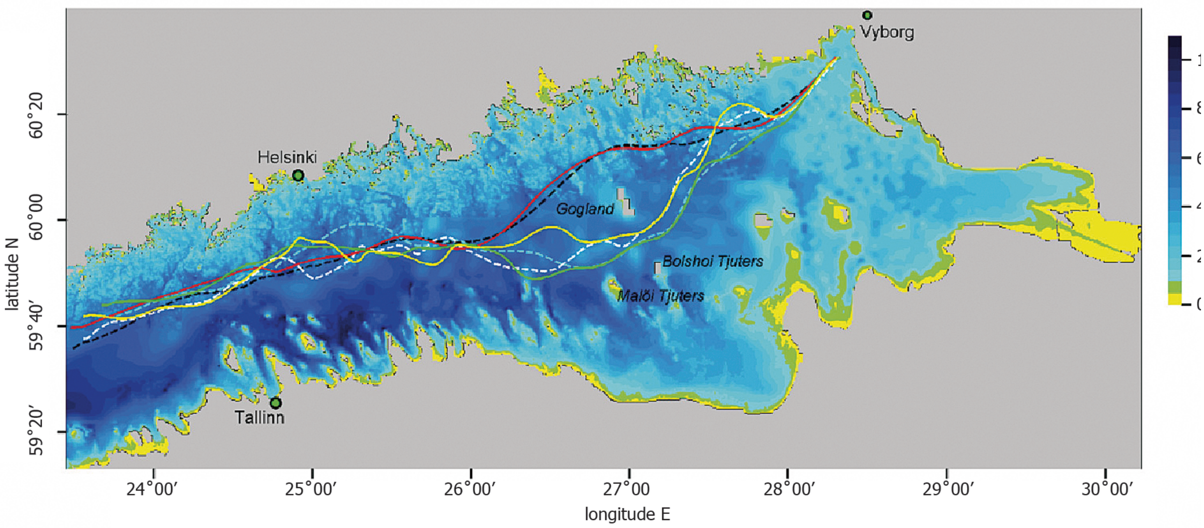
MARINE FAIRWAYS

A novel method is proposed for the optimization of marine fairways, based on the quantification of various offshore areas according to the probability of pollution released in these areas to reach vulnerable regions and tested for the Gulf of Finland. This technique is expanded to cover also South-Western Baltic Sea and Kattegat. The analysis of the potential pollution released during a ship accident and further carried by currents may affect marine protected areas in the Gulf of Finland at very large distances up to 200 km. Shifting the major fairway by a small distance in some sections may lead to a huge decrease in the amount of pollution carried to the largest marine protected area.



Environmentally optimized fairways in the Gulf of Finland

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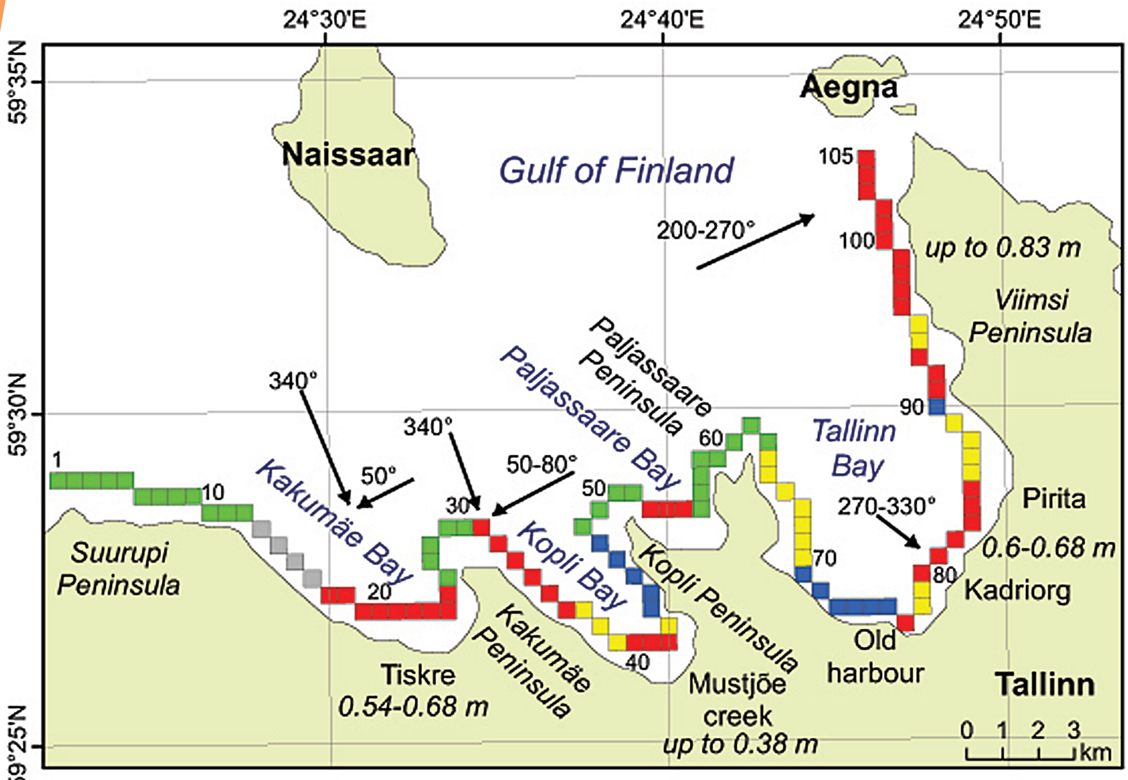
POLLUTION AND PATCHES

Inclusion of a model component for small-scale random spreading into the calculations of current-driven propagation of pollution substantially impacts the shape of single trajectories, the spreading rate of closely packed trajectories and the number of trajectories that eventually reach the coast. The pattern of most frequently hit coastal sections, the probability of hit to each such section and the time the pollution spends offshore are almost insensitive to the absence or presence of eddy-diffusivity effects. Using the concept of finite-time compressibility, the patch formation efficiency is explained in compressible flows on the example of the analysis of the surface velocity field in the Gulf of Finland. A measure of finite-time compressibility of flow fields is developed that accounts for time correlations of realistic flows and is capable to quantify the ability of clustering of passive tracers on the sea surface. The locations for spontaneous formation of surface patches are established for the Gulf of Finland through the analysis of time correlations of the convergence field and Lagrangian transport.



Areas around Tallinn potentially affected by high-wave set-up (red squares), wave propagation shown by arrows

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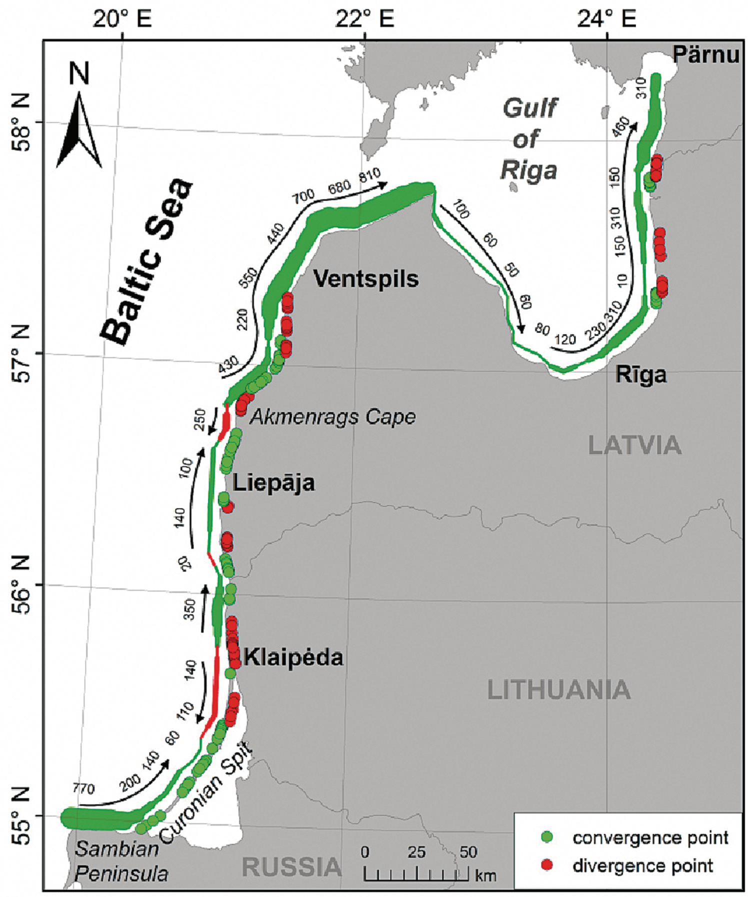
COASTAL PROTECTION AND SEDIMENT TRANSPORT

The qualitative patterns of wave-driven net and bulk sediment transport along the eastern Baltic Sea coast are very robust. The overall counter-clockwise transport contains two persistent reversals. It is shown that beach profiles may develop a two-section almost-equilibrium structure under joint impact of short wind waves and groups of long ship waves. The upper section of a profile is convex and follows the 4/3 power law at small depths and in the swash zone. The maximum wave set-up (up to 70-80 cm) forms more than 50% of all-time maximum water level and thus may serve as a substantial source of marine hazard for low-lying regions within and around Tallinn. The options for using an ensemble of projections to evaluate return periods of extreme water levels are established for selected locations of the Estonian coast. Statistical parameters of the wave inundation on a plane beach are calculated within nonlinear shallow water theory and studied experimentally. The probability of coastal floods grows with an increase in the nonlinearity of the incident wave field.



Convergence and divergence of sedimentsalong the coast of eastern Baltic Sea

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EXTREME WAVES AND TSUNAMIS

The world-wide statistics of rogue wave accidents in 2006-2010 demonstrates that the largest number of accidents occur at the coast and in the coastal zone. The rogue wave formation within nonlinear hyperbolic systems is only possible through nonlinear wave-wave and/or wave-bottom interactions. The possibility of rogue wave formation due to modular instability is shown in a basin of intermediate depth, starting from about 20 m. The distribution function of extreme run-up characteristics can be approximated by the Rayleigh distribution in a wide range of wave amplitudes and spectra even if the incident wave field is non-Gaussian. Analytical theory of tsunami generation by submarine landslides was extended to the case of narrow bays and channels of various geometries in the shallow water framework. Resonant amplification of tsunamis, induced by underwater landslides and the problems of wind set-down and set-up relaxation in inclined U-shaped bays are studied analytically within nonlinear shallow water theory. The Carrier-Greenspan transform for wave run-up on a plane beach is generalized for inclined channels of arbitrary cross-section.

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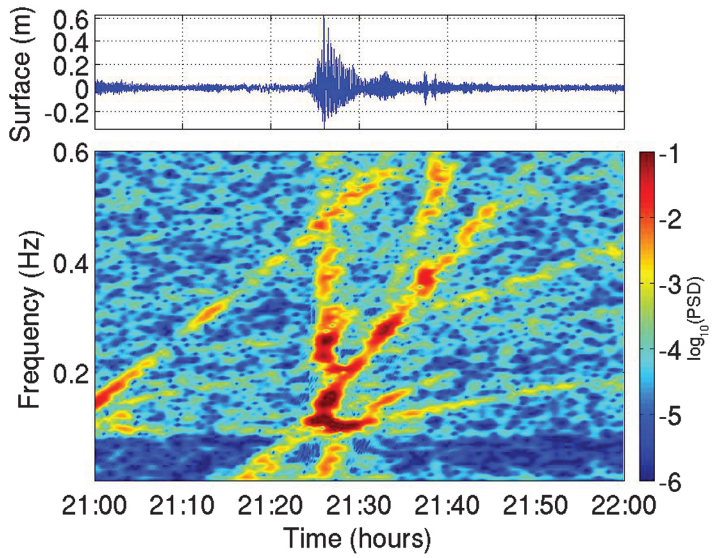
WAKE WAVES

A new mechanism producing onshore transport of substantial amounts of water remote from the fairway through wake waves generated by high-speed ferries is described based on high-resolution water surface profiling. A novel method making use of spectrogram analysis has been applied to quantify the duration, intensity and frequency distribution of wake waves from high-speed ferries and conventional ships.



Spectrogram of the wake of Tallink Star the island of Aegna (2008)

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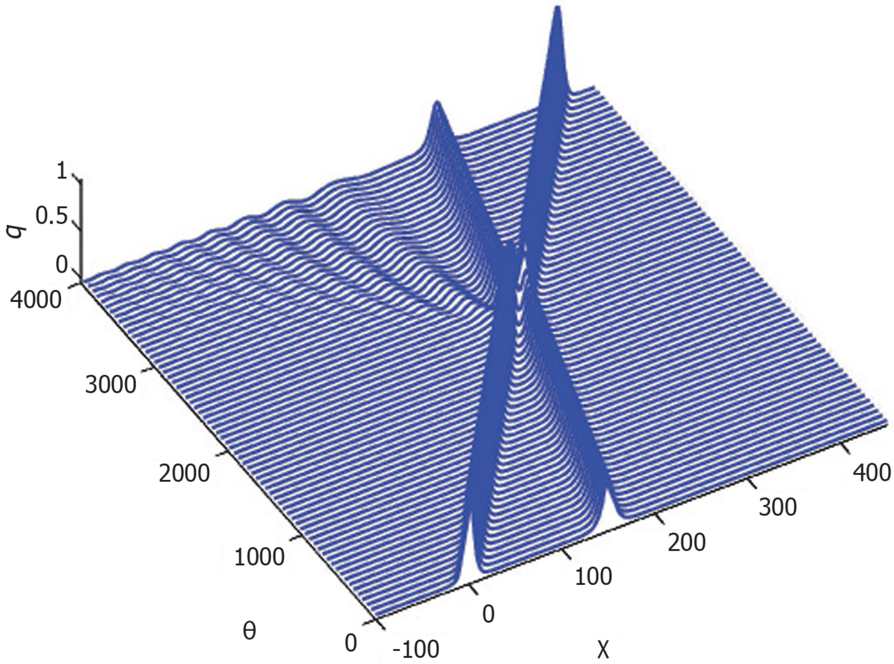
WAVE EQUATIONS

A higher-order (2+4) Korteweg-de Vries-like equation for interfacial waves is derived for a symmetric three-layer fluid and the regimes of solitary waves established. Some novel solutions are found for modified Korteweg-de Vries equations.



Shape and interaction of solitary waves

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WAVES ON SEA – WORLD-WIDE ASPECTS

Although the focus of studies has been on the Gulf of Finland and the Baltic Proper, the wave climate is studied also on the wider scale. These studies concern the tsunami run-up in Japan, Samoa, etc, marine fairways in Kattegat and the emergence of solitary waves and the waves of depression in Venice Lagoon. The last result has got wide recognition by peers.

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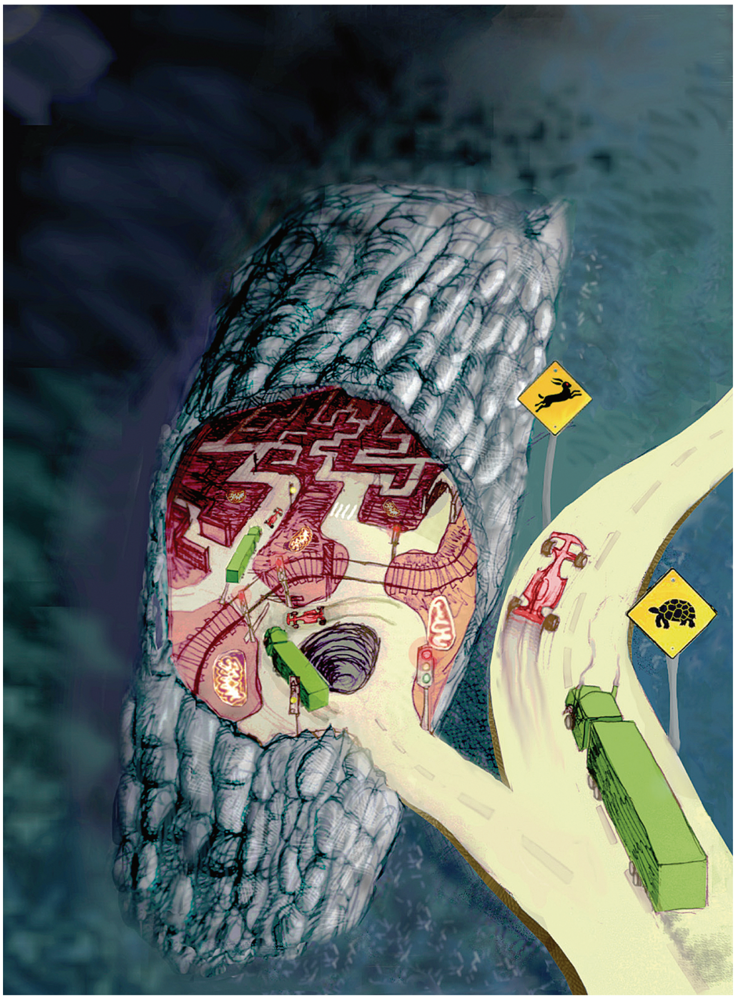
SYSTEMS BIOLOGY

MAIN ISSUES

It is proposed that local intracellular diffusion obstacles shape the energy transfer in the heart; by establishing the general mechanisms (compartmentation of cytoplasm) of single cell bioenergetics, the basis for metabolic therapy of heart failure will be formulated.



Diffusion scheme in a cell (E. Illaste)

DIFFUSION

It is demonstrated that intracellular structures impose significant diffusion obstacles in rat cardiomyocytes using a single cell preparation. Results obtained from experiments indicate that diffusion of a smaller molecule is restricted more thanthat of a larger one, when comparing diffusion in cardiomyocytes to that in the solution. The presence of periodic intracellular barriers has been suggested. It is demonstrated that the healthy heart of creatine-deficient mice is able to preserve cardiac function at a basal level in the absence of creatine kinase-facilitated energy transfer without compromising intracellular organization and the regulation of mitochondrial energy homeostasis. It is suggested that at least a part of the diffusion restriction at the mitochondrial outer membrane level is not by the membrane itself but due to the close physical association between the sarcoplasmic reticulum and mitochondria.

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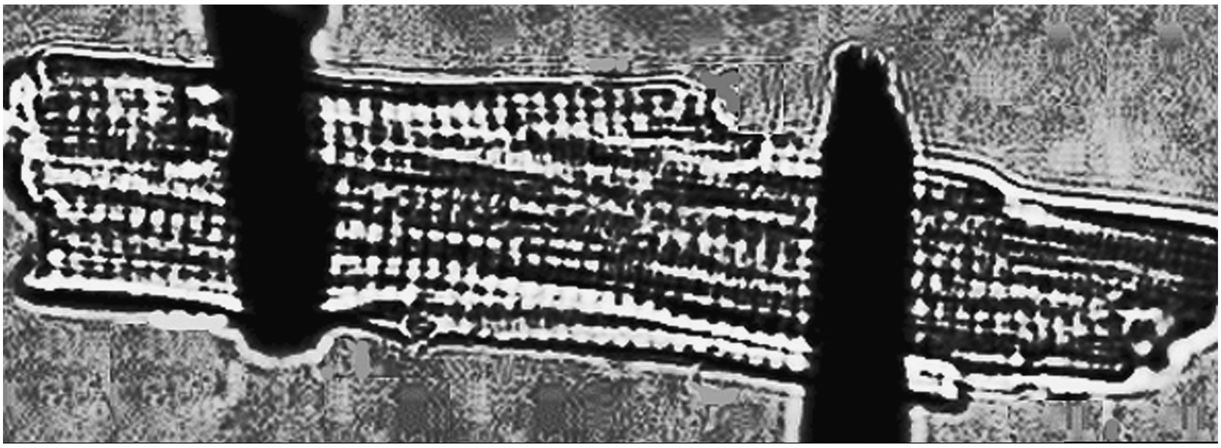
CELL ENERGETICS AND Ca^{2+} SIGNALS

The analysis of local recovery of sarcoplasmic reticulum (SR) calcium release suggests that local refilling of SR controls calcium spark amplitude recovery. It is shown that the dynamic method provides a measure of total flux and not the net flux as presumed previously. It is demonstrated that ADP potently restores calcium retention capacity in severely stressed mitochondria. This effect is most likely not related to a reduction in reactive oxygen species production. It is shown that in oxidative muscle such as a heart, some ATPases are tightly coupled to glycolysis and do not use ATP provided by mitochondria.



Loading of a heart cell in vivo for determining its energetic parameters

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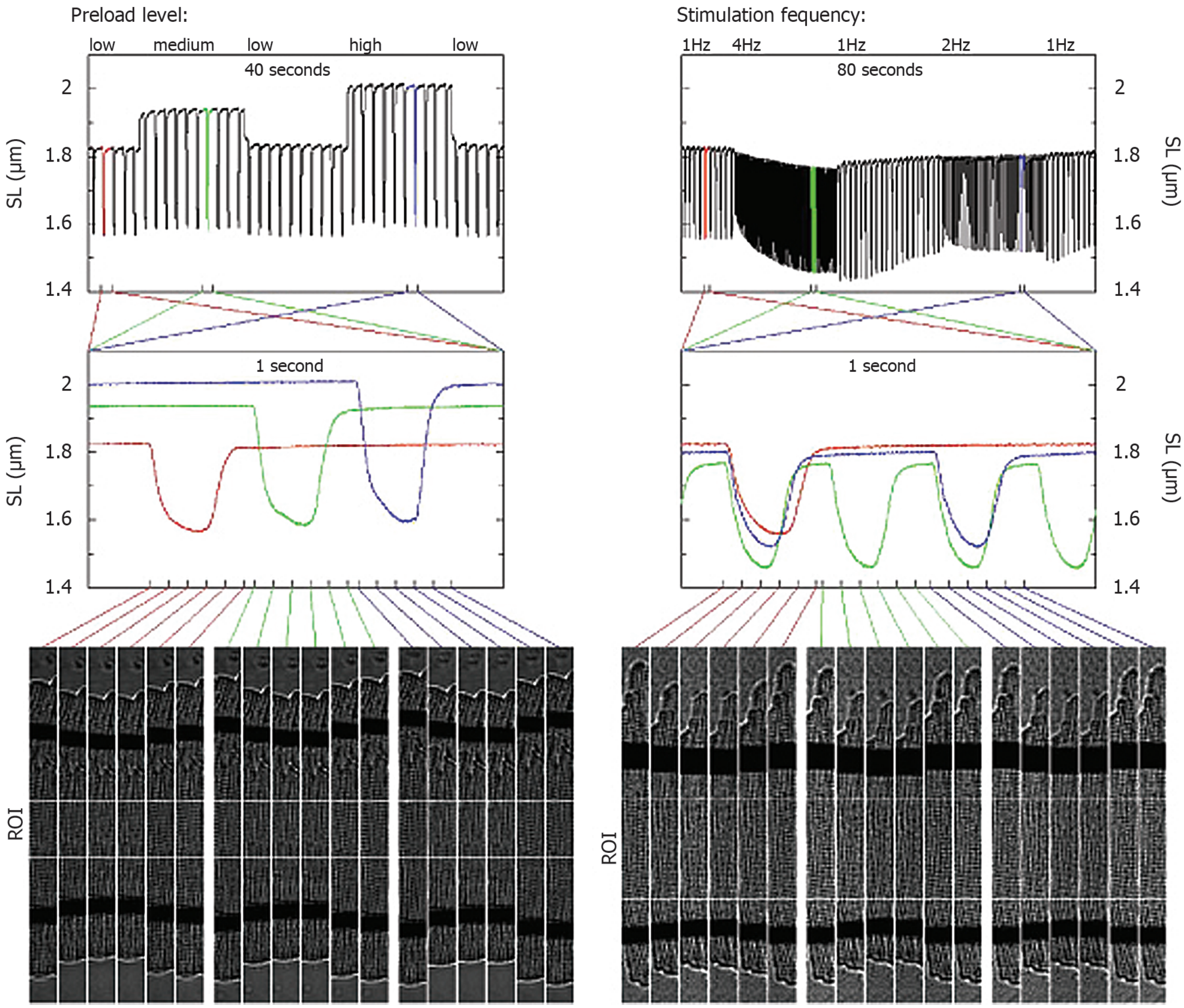
CONTRACTION

An efficient and accurate method for determining sarcomere lengths of cardiomyocyte is developed and implemented in open-source software. A cross-bridge model describing the mechanoenergetics of actomyosin interaction is developed.



Determination of sarcomere lengths in single rat cardiomyocyte experiments

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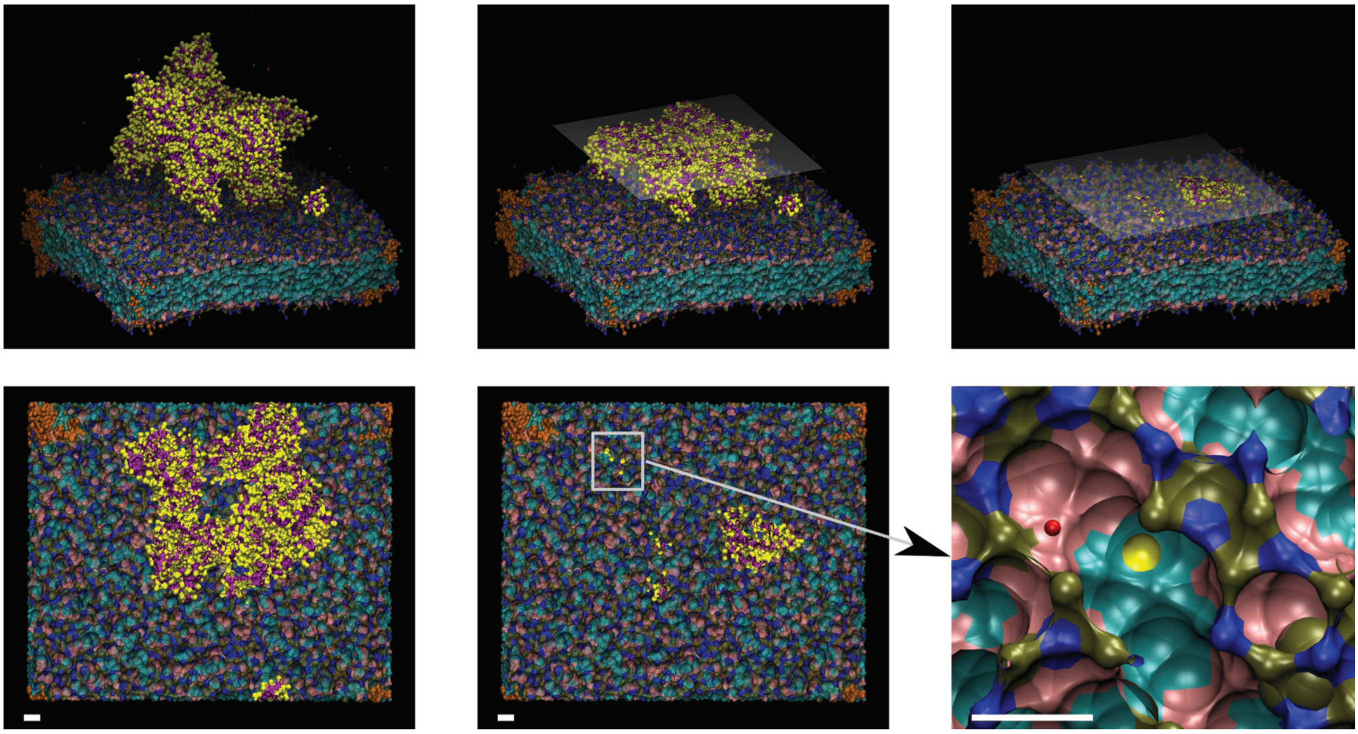
METHODS

An open-source package for deconvolution of confocal microscopy images is developed on the basis of regularized Richardson-Lucy algorithm and stopping criteria for deconvolution of images have been established. A symbolic Gauss-Jordan elimination routine for analyzing large metabolic networks has been developed.



Molecular dynamics simulation of creatine kinase

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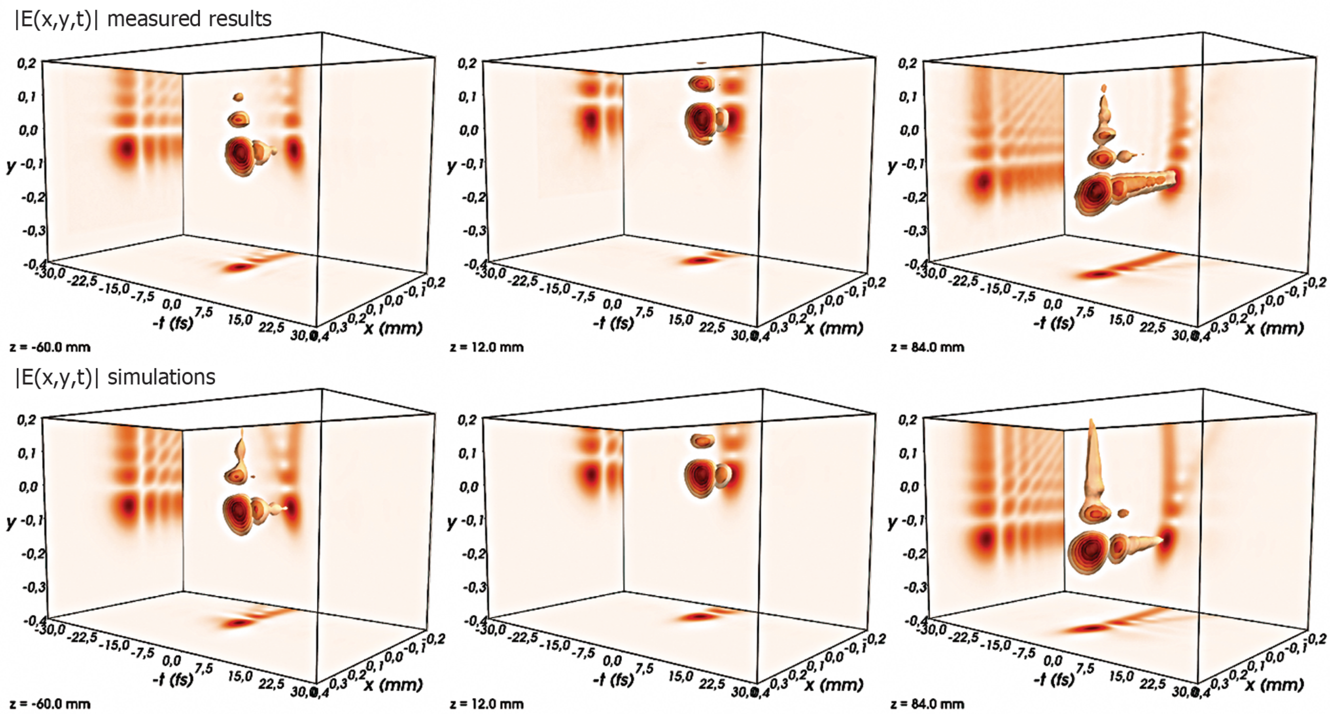
OPTICS

MAIN ISSUES

Formation of localized light bullets like Bessel-X waves and Airy-Bessel pulses by means of diffractive and refractive optical elements is theoretically analysed and experimentally realized.

LOCALIZED WAVES

The boundary diffraction wave theory is generalized and adopted for Gaussian pulses. Predictions of the theory are verified experimentally by measuring diffraction of ultrashort optical pulses on various screens. Nonlinear second-harmonic generation with laser beams transformed by internal conical refraction in a biaxial crystal is studied, and transformation of vortex Laguerre-Gauss laser beams by conical refraction several specific second-harmonic beam profiles are demonstrated. For the first time temporal focusing of ultrashort pulsed Bessel beams into Airy-Bessel light bullets by a circular diffraction grating is verified. By theoretical studies and direct measurements with ultrahigh temporal and spatial resolution it is shown that a set-up based on a spatial light modulator with an imprinted wrapped cubic phase shapes femtosecond pulses into curvilinearly propagating Airy pulses of type II, whereas a set-up based on a custom-made refractive element with a cubic phase surface profile produces type IV nondispersing Airy pulses of exceptional high quality.



Airy pulses are generated and simulated

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EXPERIMENTAL SET-UPS

A set-up for spatiotemporal measurement of ultrashort impulse responses of optical systems with up to 5-femtosecond temporal resolution is accomplished by using a supercontinuum laser source and photonic crystal fibres. For the experiments an ultra-broadband version of spectral interferometer is constructed which allows to record impulse responses with ultrahigh (single-cycle) temporal and micrometer-range spatial resolution. In 2014, the Optics Group as the whole Institute of Physics of the University of Tartu moved into the new building. The conditions to carry out experimental research in the fields of physical, nonlinear and ultrafast optics became much better.

NONLINEAR CONTROL THEORY

MAIN ISSUES

Attention is focused on novel algebraic methods and symbolic software tools for solving fundamental problems in nonlinear control. The approach is based on theory of non-commutative polynomial rings, linear algebra over the field of meromorphic functions, lattice theory and time-scale analysis. As a result, one can address general continuous- and discrete-time systems, including non-smooth systems and systems, defined on more general time scales. The software is of open access and used by researchers and graduate students world-wide.

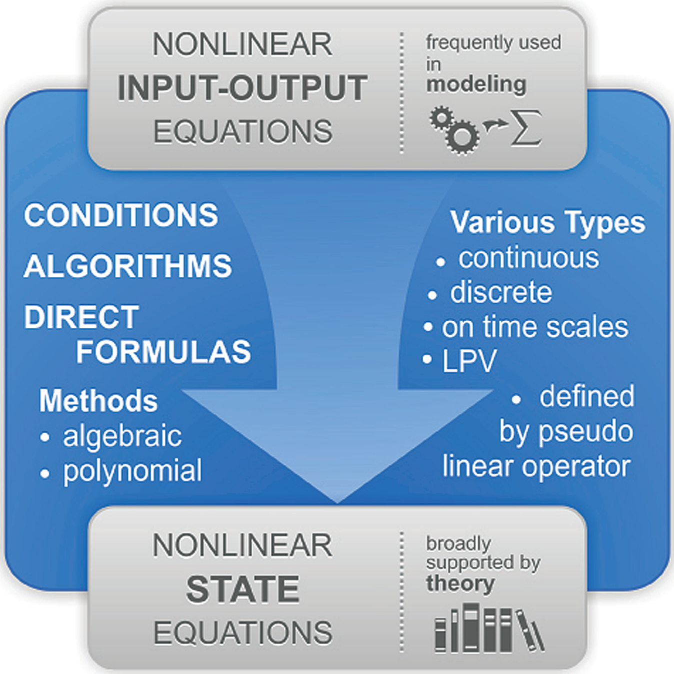
THEORY

The reduction and realisation problems are solved for nonlinear control systems applying the theory of non-commutative polynomials. The main advantage of polynomial approach is 'computability'; the theoretical results are complemented by explicit formulas yielding a short program code in Mathematica-based symbolic software. Computational aspects of realisation of a set of higher order nonlinear input/output equations in the state space form are analysed. Instead of the algorithmic solutions, provided in earlier studies, the explicit formulas, based either on the concept of adjoint polynomials or on division of polynomials, are obtained. Using the nonlinear realization theory, necessary and sufficient conditions are provided for linear parameter-varying input-output equations to be transformable into a state-space form with static dependence on the so-called scheduling parameter.

The inversive differential ring, associated with a nonlinear control system, defined on a non-homogeneous but regular time scale is constructed and equipped with three operators (delta- and nabla-derivatives and forward shift operator) with their properties determined. The developed formalism unifies/extends those for continuous- and discrete-time systems.

The inversive differential ring, associated with a nonlinear controlsystem, defined on a non-homoge-neous but regular time scale is constructed and equipped with three operators (delta- and nabla-derivatives and forward shift operator) with their properties determined. The developed formalism unifies/extends those for continuous- and discrete-time systems.

The observable space of the nonlinear system is analysed using the time scale formalism. This allows formulating the conjecture about the possible non-integrability of the observable space in



Realization problem

the discrete-time case. It has been shown that for the special subclass of reversible polynomial discrete-time systems the observable space is always integrable. The simple necessary and sufficient conditions, allowing transforming the nonlinear discrete-time control system into the extended observer form, are provided. The solvability conditions are formulated in terms of certain partial derivatives and due to the matrix representation they can be checked almost by direct inspection.

In order to address the disturbance decoupling problem by dynamic measurement feedback for discrete-time systems, the algebraic approach is applied. This approach, based on lattice theory, allows the system description also depend on non-differentiable functions. A necessary and sufficient condition is given in terms of controlled and (h,f)-invariant functions. Also, algorithms are derived which find the invariant functions and the required feedback.

In order to address the disturbance decoupling problem by the dynamic measurement feedback for discrete-time systems, the algebraic approach is applied. This approach, called the algebra of functions allows the system description also depend on non-differentiable functions. A necessary and sufficient condition is given in terms of controlled and (h,f)-invariant functions. Also, algorithms are derived which find the invariant functions and the required feedback. Using the nonlinear realization theory, necessary and sufficient conditions are provided for linear parameter-varying input-output equations to be transformable into a state-space form with static dependence on the so-called scheduling parameter. The observable space of the nonlinear system is analysed using the time scale formalism. This allows formulating the conjecture about the possible non-integrability of the observable space in the discrete-time case.

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APPLICATIONS

A distributed planning and control framework for human assistive robots is developed and its prototype implemented for Scrub Nurse robot constructed and used by Mijawaki Laboratory in Tokyo Denki University. The application of Neural Networks based Additive Nonlinear Auto Regressive eXogenous (NN-ANARX) models as a computational tool of the supervision system for therapeutic exercises is proposed.

SEMINAL RESEARCH PAPERS

SEMINAL RESEARCH PAPERS

A. Illaste, M. Laasmaa, P. Peterson, M. Vendelin. Analysis of molecular movement reveals latticelike obstructions to diffusion in heart muscle cells. Biophys. J., 2012, 102(4), 739-748.

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GENERAL PUBLICATIONS

MONOGRAPHS

J. Janno, J. Engelbrecht. Microstructured Materials: Inverse Problems. Springer, Berlin, 2011.

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OVERVIEWS

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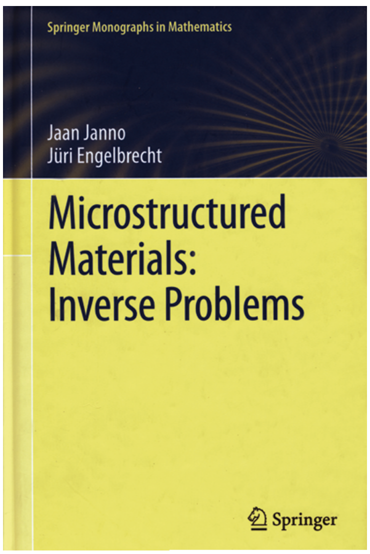
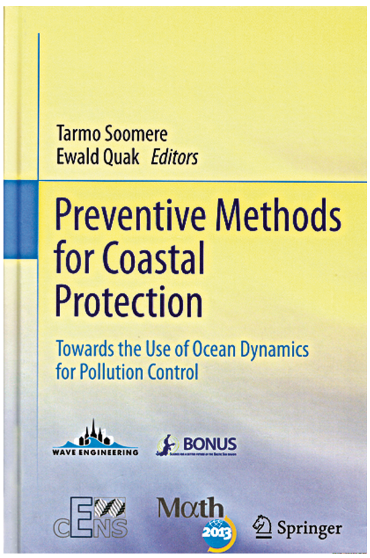
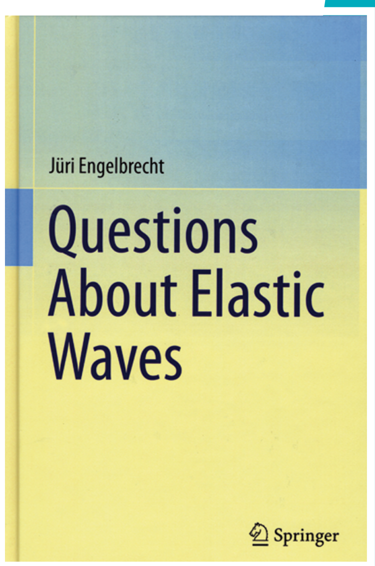




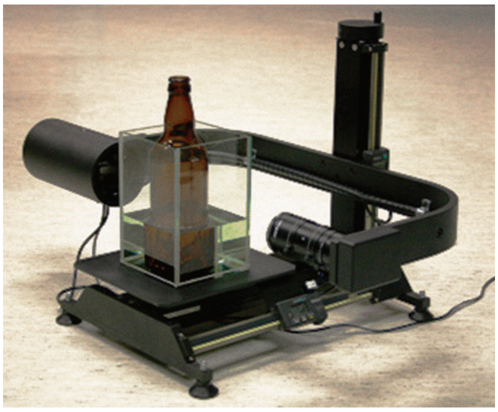


LABORATORY BASIS

LABORATORY OF PHOTOELASTICITY

Equipped with original transmission polariscopes and scattered light polariscopes SCALP.

Spin-off company GlasStress Ltd produces and sells original devices to industry (the number of clients for transmission polariscopes is about 50 and for scattered light polariscopes – about 100).



Polariscope AP-7

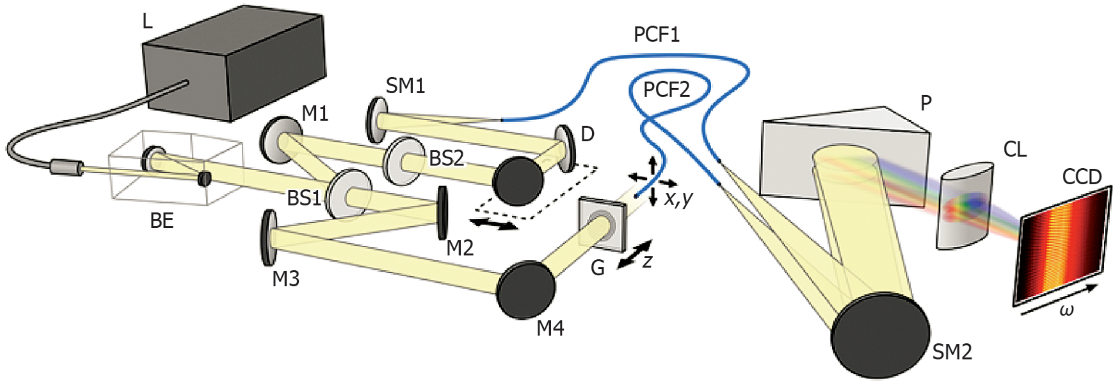
SYSTEMS BIOLOGY

Laboratory has a special wet laboratory room and two microscopy rooms in the Institute of Cybernetics. The laboratory has been equipped using funding from Wellcome Trust and European Union initiatives. There are two widefield fluorescence microscopes with single-cell mechanics and electrophysiology setups, a photon counting confocal microscope, respiration chambers, and absorbance spectrophotometer. This is practically all the major equipment that is needed for the research and there is an access for the additional required equipment in the campus of the TUT, such as spectrofluorometer, HPLC, and confocal microscope optimized for imaging. There is the access to a high-performance computer cluster in the TUT which has been built taking into account the requirements of CENS. The microscopes have been custom designed and programmed using a software platform developed in the group (see below Software section). This platform provides the freedom to control and automate the course of various experiments and extend our setups. With two fluorescence microscopes, there are dedicated single-cell mechanics and electrophysiology setups. In addition, a new setup for measuring energetics of the working isolated heart is developed to follow regional heterogeneities in mechanical work and oxygen consumption.

OPTICS

In the Laboratory of physical optics (UT) basing on a technique SEA TADPOLE of characterization of ultrashort light pulses, and with the help of cutting edge technology, an original and very versatile interferometer for characterizing response of optical elements was built. With the help of supercontinuum laser radiating spatially coherent ultrabroadband light, optical coherence theory and endlessly single mode fibres, its spectral range spans from 400 up to 1000 nm and, accordingly, the temporal resolution is about few femtoseconds. In visible regions this is the absolute limit of one cycle duration. The advanced setup together with computer controllable phase modulator array and custom made optical elements (either etched or free-form polished) made possible observing of nondiffractive and curvilinearly propagating Airy pulses and temporal focusing effects with unprecedented few micron spatial and single-cycle temporal resolution.

The beam from the laser L is expanded by a reflective beam expander BE and then sampled into the reference arm of the interferometer by an UV fused silica window BS1, directed by mirror M1 through a beam splitter dispersion compensation plate BS2 and a variable delay line D, and focused by a spherical mirror SM1 into fiber PCF1. On the measurement arm the light is directed with mirrors M2-4 onto circularly symmetric diffraction grating G and the resulting field is



Interferometric set-up (acronym OCEAN TADPOLE)

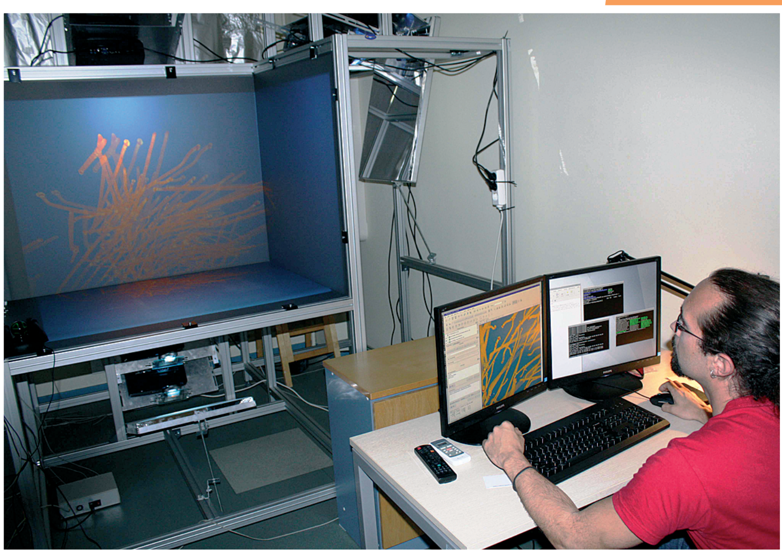
sampled by the fiber PCF2. The output of the fibers is placed on the entrance slit of an imaging spectrometer with a few mm separation, so that light enters the spectrometer under a small angle 2θ perpendicular to the frequency axis ω. Spectrometer consists of a spherical mirror SM2, reflecting half-prism P, uncoated FS cylindrical lens CL and a CCD camera. Spatial interference pattern on the CCD camera is processed to retrieve the spectral phase and amplitude information of the field correlation function. Optical fibers allow effortless redesign of measurement set-up while keeping the most alignment-critical part–the spectrometer–intact.

LABORATORY OF WAVE ENGINEERING

The Wave Engineering Lab makes use of the Baltic Sea and its coasts as an excellent natural laboratory. The roughest wave conditions on the southern coast of the Gulf of Finland until 2012 were measured and wave regime in Lake Peipsi quantified using pressure-sensor-based autonomous wave recorders. High-resolution water surface position samples from short-range acoustic devices have led to principally new understanding of the structure of wakes from fast ferries and the shapes of small-amplitude rogue waves. Differential GPS devices, various purpose-built tools designed to record wave run-up properties and scanning laser distance meters contribute to the understanding of how exactly the waves shape our coasts down to the level of impact of single waves. Several unique remote and contact wave run-up recorders have been custom-built for our needs. Two compact current meters capable of working in the surf zone report extreme water velocities in this highly energetic environment. Dozens of autonomous drifters provide unique information about Lagrangian transport in the marine surface layer.

3D VISUALIZATION

The Virtual Reality environment Kyb3 is available using ParaView, Blender CAVE and VRUI-based software. Flexible software A.C.T.I.V.E. and MedImVR are developed and applied for visualization.



The Virtual Reality environment Kyb3

APPLICATIONS

Scattered light polariscope SCALP
For stress measurements in architectural glass panels and automotive glazing

Transmission polariscope
For stress measurement in glass containers, tubes, pharmaceutical ampullas and tableware

Virtual 3D Reality Environment
For 3D analysis together with the software A.C.T.I.V.E., MedImVR and TANS

Spectral interferometer
For recording impulse responses with ultrahigh temporal and micrometer-range spatial resolution

Optimal marine fairways in the Gulf of Finland proposed

Models for determination of pollution patches elaborated

SOFTWARE

Responsible: P. Peterson, PhD

F2PY: Fortran to Python Interface Generator, an automatic tool to connect high-level Python scripting language and high-performance Fortran/C libraries and programs. F2PY is a part of NumPy package (http://www.scipy.org). The original F2PY site: http://cens.ioc.ee/f2py2e

Scipy: ScientificScientific Python, a collection of a variety of high-level science and engineering modules for Python; (http://www.scipy.org)

N-dimensional array manipulators in Python (http://www.scipy.org)

Software to control a Strathkelvin 929 Oxygen System;
http://code.google.com/p/iocbio/wiki/IOCBioStrathKelvin

Development of a multi-platform tool for analysing fluorescence vs. time data (LSJuicer);
http://code.google.com/p/lsjuicer/

Python wrapper to the C++ Deconv library by Y. Sun et al. (see details in J. Microscopy, 2009, 236, 3,180-193); http://code.google.com/p/pylibdeconv/

Continued development of the PyLibTiff package;
http://code.google.com/p/pylibtiff/ - cont

Continued development of IOCBio Sarcomere length and fundamental period software;
http://code.google.com/p/iocbio/wiki/IOCBioSarcomereLength

Continued development of C++ software for executing experiment protocols on fluorescence and confocal microscopes; http://code.google.com/p/iocbio/wiki/IOCBioMicroscope

Responsible: H. Herrmann, PhD

A tool for Virtual Reality visualization for Steel Fibres Reinforced Concrete A.C.T.I.V.E.:
http://bitbucket.org/VisParGroup/active

Fibre orientation analysis from CT volumes (uTANS):
https://bitbucket.org/VisParGoup/utans-fib

A package to calculate alignement tensors and the orientation distribution function:
https:/bitbucket.org/vispar/alignement

OTHER ACTIVITIES

CONFERENCES

Intense Day on Recent Problems on Dispersive waves (06.12.2011). Chair: J. Engelbrecht

Session on Complex Systems, Scientific Council of the State President of Estonia (24.03.2011). Chair: J. Engelbrecht

Seminar on Complexity and Crisis Management in Society and Environment (28.05.2012). Chair: T. Soomere

Workshop on Measurement, Visualization, Modelling and Simulation of Complex and Microstructured Materials (05-06.06.2012). Chair: H. Herrmann

Intense Day on Waves in Fluids (24.09.2012). Chair: T. Soomere

The 10th Eurographics Symposium on Geometry Processing (16-18.07.2012). Chair: E. Quak

The 43rd International Physics Olympiad (15-24.07.2012), Tallinn, Tartu. Steering Committee member: J. Kalda

Intense Day on Waves and Climate Tolerance (08.11.2013). Chair: T. Soomere

Intense Day on Marine Research (03.03.2014). Chair: T. Soomere

IUTAM Symposium on Complexity of Nonlinear Waves (08-12.09. 2014). Co-Chairs: A. Salupere, G. A. Maugin

Intense Day on Coastal Science (22.09.2014). Chair: T. Soomere

Intense Day on Marine Science (08.12.2014). Chair: T. Soomere

Intense Day on Marine Research (27.01.2015). Chair: T. Soomere

The 28th Nordic Seminar on Computational Mechanics (22-23.10.2015). Chair: A. Berezovski

Conferences Elsewhere

The 2nd Baltic Way Annual meeting (11-13.04.2011), Palermo, Italy. Chair: T. Soomere

Euromech 540: Advanced Modelling of Wave Propagation in Solids (01-04.10. 2012), Prague, Czech Republic. Co-Chairs: R. Kolman, A. Berezovski

Special Section on Localized Waves, the 34th Progress in Electromagnetics Research Symposium (PIERS) (12-15.08.2013); Stockholm, Sweden. Chair: P. Saari

RESEARCHERS FROM OTHER COUNTRIES

Researchers from Denmark, Germany, Norway, Russia, Trinidad and Tobago, Latvia are working permanently in CENS, PhD students and post-docs are/were from Italy, Russia, Lithuania, Latvia, Poland, Mexico, etc.

Researchers for short-time studies include visitors from Australia, India, USA, Hungary, Italy, Germany etc.

CENS POSTDOCS ABROAD

J. Belikov (Israel), M. Eik (Finland), A. Illaste (Switzerland), T. Mullari (Austria), T. Peets (Hong Kong), H. Ramay (Switzerland),

OTHER ACTIVITIES

HONOURS (from 2011 on)

State research awards

J. Janno. Inverse problems in non-destructive testing 2012, exact sciences

T. Soomere. Managements of hazards from the Baltic Sea 2013, technical sciences

J. Engelbrecht 2015, for life-long research

State Decorations

A. Salupere, White Star IV Class, 2013

J. Kalda, White Star V Class, 2013

T. Soomere, White Star III Class, 2014

Other awards and recognitions

T. Soomere, Estonian award for research popularisation, 2011

P. Saari, Denisjuk medal from Russian Roždestvenski Optical Society, 2011

P. Saari, World Cultural Council's Special Recognition diploma, 2011

P. Saari, OSA senior member, 2011

T. Soomere, Best scientist of TUT, 2012

T. Soomere, Medal of Baltic Academies for results in marine sciences, 2013

J. Kalda, State President Award for teaching physics, 2013

P. Saari, Honoured Citizen of Tartu, 2014

J. Engelbrecht, Foreign member of the Academy of Sciences in Turin, 2015

J. Engelbrecht, Professor of interdisciplinary studies in Person Centered Approach Institute collaborating with the WHO (Rome), 2015

H. Aben, J. Anton, German industrial award for Estonian companies, 2015

A. Valdmann, A. Remm, R. Matt. First prize in the category of photonic technologies, Open Research Challenge, Friederich-Alexander University, Erlangen, Germany, 2015

Members of the Estonian Academy of Sciences

H. Aben, J. Engelbrecht, P. Saari, T. Soomere

Humboldt Fellows

J. Engelbrecht, T. Soomere, E. Quak, H. Herrmann, I. Didenkulova

Wellcome Trust Fellow

M. Vendelin

PROMOTED PhDs IN 2011–2015

1. T. Peets. Dispersion analysis of wave motion in microstructured solids. PhD thesis, TUT Press, Tallinn, 2011.
2. K. Tamm. Wave propagation and interaction in Mindlin-type microstructured solids: numerical simulation. PhD thesis, TUT Press, Tallinn, 2011.
3. A. Errapart. Photoelastic tomography in linear and nonlinear approximation. PhD thesis, TUT Press, Tallinn, 2012.
4. J. Belikov. Polynomial methods for nonlinear control systems. PhD thesis, TUT Press, Tallinn, 2012.
5. O. Kurkina. Nonlinear dynamics of internal gravity waves in shallow seas. PhD thesis, TUT Press, Tallinn, 2012.
6. A. Illaste. Analysis of molecular movements in cardiac myocytes. PhD thesis, TUT Press, Tallinn, 2012.
7. D. Schryer. Metabolic flux analysis of compartmentalized systems using dynamic isotopologue modeling. PhD thesis, TUT Press, Tallinn, 2012.
8. M. Kääramees. A symbolic approach to model-based online testing. PhD thesis, TUT Press, Tallinn, 2012.
9. I. Didenkulova. Long wave dynamics in the coastal zone with application to marine induced hazards. DSc thesis in Physics and Mathematics, Oceanography. P. P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia, 2013.
10. A. Rodin. Infuence of wave breaking effects on long wave transformation and runup on a beach. Cand. Sci. thesis in Physics and Mathematics, Fluid Mechanics. Nizhny Novgorod State Technical University, Nizhny Novgorod, Russia, 2013.
11. M. Sepp. Estimation of diffusion restrictions in cardiomyocytes using kinetic measurements. PhD thesis, TUT Press, Tallinn, 2013.
12. P. Piksarv. Spatiotemporal characterization of diffractive and non-diffractive light pulses. PhD thesis. University of Tartu Press. Tartu, 2013.
13. V. Kaparin. Transformation of nonlinear state equations into observer form. PhD thesis, TUT Press, Tallinn, 2013.
14. I. Zaitseva-Pärnaste. Wave climate and its decadal changes in the Baltic Sea derived from visual observations. PhD thesis, TUT Press, Tallinn, 2013.
15. D. Kartofelev. Nonlinear sound generation mechanisms in musical acoustics. PhD thesis, TUT Press, Tallinn, 2014.
16. B. Viikmäe. Optimising fairways in the Gulf of Finland using patterns of surface currents. PhD thesis, TUT Press, Tallinn, 2014.
17. M. Viška. Sediment transport patterns along the eastern coasts of the Baltic Sea. PhD thesis, TUT Press, Tallinn, 2014.
18. N. Delpeche-Ellmann. Circulation patterns in the Gulf of Finland applied to environmental management of marine protected areas. PhD thesis, TUT Press, Tallinn, 2014.
19. M. Eik. Orientation of short steel fibres in concrete: measuring and modelling. Doct. thesis, Aalto University and PhD thesis Tallinn University of Technology. Aalto Univ. Press, Helsinki, 2014.
20. A. Giudici. Quantification of spontaneous current-induced patch formation in the marine surface layer. PhD thesis, TUT Press, Tallinn, 2015.
21. A. Rodin. Propagation and run-up of nonlinear solitary surface waves in shallow seas and coastal areas. PhD thesis, TUT Press, Tallinn, 2015.
22. E. Pastorelli. Analysis and 3D visualisation of microstructured materials on custom-built virtual reality environment. PhD thesis, TUT Press, Tallinn, 2015.
23. N. Karro. Analysis of ADP compartmentation in cardio-myocytes and its role in protection against mitochondrial permeability transition pore opening, PhD thesis, TUT Press, Tallinn, 2015.
24. M. Kalda. Mechanoenergetics of a single cardiomyocyte. PhD thesis, TUT Press, Tallinn, 2015.

COOPERATION

MAIN PARTNERS

University of Paris 6, Institute d'Alembert, France
University of Turin, Faculty of Mathematics, Italy
Budapest University of Technology and Economics, Hungary
Wigner Research Centre for Physics, Budapest, Hungary
Institute of Hydrodynamics, Academy of Sciences, Prague, Czech Republic
International Research Center for Mathematics and Mechanics of Complex Systems, Cisterna di Latina, Italy
University of Magdeburg, Institute of Mechanics, Germany
Worcester Polytechnical Institute, Faculty of Mathematics, USA
INSA Centre of Val de Loire, France
University of South-Maine, USA
Institute of Applied Physics, Russian Academy of Sciences, Nijni-Novgorod, Russia
Nijni Novgorod State Technical University, Nijni-Novgorod, Russia
Helmholtz Centre, GKSS Geestacht, Germany
Klaipeda University, Lithuania
James Cook University, Townsville, Australia
Sungkyunkwan University, Suwon, Korea
Korean Ocean Research&Development Institute, Korea
Institute de Recherche sur les Phenomenes Hors Equilibre, Marseille, France
University College London, UK
Université des Antilles et de la Guyane, Guadeloupe, France
Chemnitz Technical University, Germany
Aalto University, Helsinki, Finland
École Central de Nantes, France
Georgia Institute of Technology, USA
Max Planck Institute for the Science of Light, Erlangen, Germany
Bialystok University of Technology, Poland
Institut de Recherche en Communications et Cybernétique, Nantes, France
INRIA, Orsay, France
University of Limoges, France
Kyoto University, Japan
Far Eastern Federal University, Vladivostok, Russia
Johannes Kepler University of Linz, Austria
Slovak University of Technology, Slovakia
Kalasalingam University, India

COOPERATION PROGRAMMES

Estonia – Poland (Academies)
Estonia – Bulgaria (Academies)
Estonia – Hungary (Academies)
Estonia – Czech Republic (Academies)
Estonia – French (Parrot programme)

COOPERATION FOR APPLICATIONS

GlasStress Ltd cooperation with companies Nippon Electric Glass (Japan), Rudolph Instruments (USA), Pilkington (UK)

COOPERATION IN ESTONIA

Estonian Marine Institute, University of Tartu

Marine System Institute, Tallinn University of Technology

Institute of Ecology, Tallinn University

City of Tallinn (coastal zone management)

Institute of Physics, University of Tartu

TEACHING

COURSES IN TUT (selected)

Continuum mechanics – A. Salupere

The basic course for all majoring in technical physics and design of engineering structures

Nonlinear dynamics – J. Engelbrecht, D. Kartofelev

The basic course on nonlinear dynamics together with complex systems

Mathematical modelling – J. Engelbrecht, T. Peets

The course on how to tackle real problems using the tools of mathematics

Coastal engineering – T. Soomere

The main course on wave dynamics together with protection and managements of coasts

Scientific programming with Python – P. Peterson

Thermodynamics – J. Kalda

COURSES IN UT

Quantum mechanics, Advanced quantum mechanics, Quantum computing – P. Saari

Quantum mechanics, MSc course – M. Selg

Physics and technology, lectures of optics – H. Valtna-Lukner

Optics, practical course – P. Piksarv, A. Valdmann

Solitons – J. Kalda

INTERNATIONAL

International Summer School on Preventive Methods for Coastal Protection (18-20.09. 2011), Klaipeda University, Klaipeda, Lithuania. Supervisor: T. Soomere

Materials: SECREMO courses published: Environmental Mathematical Modelling for Wave Dynamics; Coastal processes and Environmental Management

Tallinn Glass Stress Summer Schools, 2011, 2012, 2013, 2014, 2015. Supervisor: H. Aben

Compendium "Photoelasticity of Glass" on CD ROM

Courses in TU Chemnitz: H. Herrmann

Simulation of New Materials; Simulation of Processes in Natural Sciences

INTERNATIONAL PHYSICS OLYMPIADS

J. Kalda has been tutoring Estonian High School students for the International Physics Olympiads since 1994. In 2012, the 43rd Physics Olympiad was hosted by Estonia (Tartu, Tallinn), where J. Kalda with his PhD students were the members of the Academic Committee and he himself was a member of the Steering Committee. His teaching materials are used not only by Estonian students, but available in English (some of these have been translated into Arabic, Portuguese and Indonesian), see, for example:

kinematics	http://www.ioc.ee/~kalda/ipho/kin_ENG.pdf
mechanics	http://www.ioc.ee/~kalda/ipho/meh_ENG.pdf
circuits	http://www.ioc.ee/~kalda/ipho/e-circuits.pdf
wave optics	http://www.ioc.ee/~kalda/ipho/waveopt.pdf
formulas	http://www.ioc.ee/~kalda/ipho/formulas.pdf

also in Indonesian and Portuguese:
http://www.ioc.ee/~kalda/ipho/Rumus-rumus%20untuk%20IPhO%20-%20Kalda.pdf
http://www.ioc.ee/~kalda/ipho/formulasheet-pt_br1.0.pdf

POPULARISATION

Numerous articles on mechanics, marine science and complex systems are published in magazines "Horisont", "Akadeemia" and others (J. Engelbrecht, T. Soomere, R. Kitt et al). Talks at summer schools (A. Salupere, J. Engelbrecht, T. Soomere, J. Kalda) are given as well as broadcast talks in the TV and radio. The texts on complexity and chaos are included into the workbook on Estonian language for High Schools (2013).

Several interviews and articles on optical science have been published in the nation-wide newspaper "Posti-mees" (H. Lukner, P. Piksarv, P. Saari). Numerous public talks and science theatre performances addressed to youth have been given (H. Lukner, K. Reivelt, A. Valdmann). In every year live referee service has been given to weekly TV contest "Rakett 69" on science for schoolchildren (H. Lukner).

Recent popular overviews

J. Engelbrecht. Complex systems with and around us. Horisont, 2/2014 (in Estonian).

T. Kändler, J. Engelbrecht (eds). Keeruka maailma võlu (Charm of Complex World), CENS, Tallinn, 2015 (in Estonian).

JÜRI ENGELBRECHT

KOMPLEKSSÜSTEEMID meis ja meie ümber

Kogu maailmas pühendatakse üha enam uuringuid komplekssüsteemidele. Tähelepanu on tingitud asjaolust, et inimkond on hakanud aru saama Ameerika kirjaniku ja futuristi Alvin Toffleri kolme aastakümne tagusest hoiatusest. See pärineb saatesõnast Ilya Prigogine'i tervikut käsitlevale raamatule: „Üks kõige arenenum tänapäeva lääne tsivilisatsiooni oskusi on tükeldamine, s.o probleemide lahkamine nende kõige väiksemateks komponentideks. See oskus on meil ülihea. Nii hea, et sageli unustame panna osad tagasi tervikuks."

28 ■ horisont 2/2014

BACKGROUND IDEAS

From earlier expert evaluation

(on the Work Plan)

"When a physical, biological, or engineering problem is reduced to its bare foundations, the result in each case is a mathematical model with partial differential equations (pde) and there are only a handful of such pde's. .... the same mathematical (and computer) methods apply to all the apparently widely different areas of research.... "

"...it is expected that the CENS will achieve more than the sum of different groups separately."

On complexity

(S. Bishop, IAB of CENS)

I will start my report of the activities of CENS by saying a few words about **complexity**. I do this for two reasons. Firstly, once we go beyond studies looking at simple nonlinear systems then we will surely encounter system outcomes that had not been predicted and therefore could be classified as resulting from complexity. Secondly, many centres around the world started life as centres of nonlinear systems but have adapted and embraced the complexity element, partly due to scientific reasons and partly due to funding.

To be clear, here is my definition of complexity. Complexity effectively describes the outcomes of mathematical complex systems**.** I would have preferred a new word to have been used (for instance the word soliton was a new word to describe a mathematical behaviour), but it appears we are stuck with it, rather like we are with the word chaos for a specific behaviour of nonlinear systems (but that is another story). Anyway, for me, complexity is the study of systems that:

- are dynamical
- involve a number of interacting parts (also called components, entities or agents)
- usually the interactions are nonlinear in their effect of each other with feedback between the parts
- produce system outcomes which are more than the sum of the outcomes of the parts

This last point means that the usual reductionist approach that science has adopted over the centuries simply does not work. Even knowing the detailed behaviour of the parts by themselves is not enough to tell you the behaviour of the system as a whole when all the parts are linked. Looking back we can now classify known behaviours, such as synchronisation or phase shifts, as being outcomes of complex systems. However, typically today the types of system studied around the world often have large numbers of interacting parts and, whereas previously most early studies focused on systems made up of simple components, today models include components that require many variables to describe their responses to various situations. For instance, it has been possible to reproduce the complicated patterns that we see when large groups of birds flock together (in starlings this is called murmurations) using just three simple, well defined rules (attraction, cohesion and repulsion) which govern the behaviour of all the birds in the flock.

On the other hand, when applied to social systems each agent can have their own set of rules, which govern how they behave and respond to the environment about them, so that the number of rules can be large. In the new field of computational social science such methods are often called agent based models. In many cases, including in economic considerations, the rules are not even deterministic with the inclusion of the so-called irrational agent almost being a requirement to try and match human behaviour.

These models are more heuristic for most people, replacing complicated differential equations with simple rules that can be understood by anyone. What is more, their outcomes lend themselves to natural forms of visualisation. Given data on previous system behaviour allows us to tune parameters so that the models can be used in a predictive sense. However, as pointed out by my colleague Roger Grimshaw, the power of the mathematical model is not really that it can be used in a predictive sense but instead that it allows us to *understand* system behaviour. This is very important since it is more than likely that more than one system output is possible and it then becomes a matter of deciding which of the outcomes is more likely than others.

It would be interesting to see how the activities of CENS could be enhanced by considerations of such wider studies of complexity, or indeed contribute to the field. Despite the focus elsewhere on numerical treatments there is still a need to understand the components and how they interact with each other. Hence the work carried out by CENS in the biology area is still a vital component. Furthermore, the work in control on algebraic methods again is a vital element since we need theoretical treatments to frame other numerical work. Another area in which there is considerable research interest is the behaviour of networks where graph theory is brought to bear on system behaviour.

The whole is more than the sum of the parts.

Aristotle

SUMMARY OF ACTIVITIES

The research in CENS over 2011-2015 (and earlier) described within this Report followed the recommendations of experts which coincide with the ideas of the Action Plan of CENS. Moreover, the ideas on complexity explained by Steven Bishop (see Background Ideas) are closely related to the research philosophy of CENS over many years and especially followed during 2011-2015. Surely, the idea is extracting the essentials from complicated models and observations but not forgetting the whole. Indeed, the focus on **nonlinear dynamical processes** with due attention to accompanying effects like dispersion, dissipation and diffusion is kept in all the studies. In these studies, the crucial issue is the analysis of interactions: wave-wave type, wave-field type, wave-internal structure type and their combinations in order to understand the physical mechanisms which govern the processes, let them be in solids, fluids or tissues. The nonlinear mathematical models, as a rule, are based on the theory of continua. This is the joint basis and often leads to similar basic governing equations. From the results described above, it is clearly seen that conventional theories must often be improved or modified in order to grasp physical phenomena with a proper accuracy. As far as the models are inherently nonlinear, the numerical methods must also be modified like for simulation of waves in solids, for unification of concepts of discrete and continuous time, for diffusion problems, etc. In this context, the nonlinear control theory is of importance.

Many results reflect the **synergy** between various disciplines: interaction of solitons in solids and fluids, contraction of muscles in tissue mechanics and links to internal variables, formation of patches of pollution on the sea using the knowledge from currents and soft matter physics, formation of diffraction patterns and localized waves which are characteristic in optics but also in solids, wave propagation in channels (fluids) and in laminated materials (solids), modelling of social systems for which the methods of soft matter physics are used (graph theory for modelling fiscal transactions), modelling mechanical waves in biomembranes combining physiology and mechanics of solids. Such studies will be continued. It is obvious that due to interactions new patterns of waves or fields emerge which are clear signs of complexity. Beside these specific results, some published papers are directly related to general complexity problems in engineering and natural sciences. In addition, the algorithms for nonlinear control theory are derived paying attention to various timescales and unifying the discrete and continuous time. This is important for understanding real dynamical processes.

Although the main research results are published in leading journals and conference proceedings, several monographs authored by CENS Fellows are also published by international publishers. Although the main research of CENS is directed to fundamentals of nonlinear science, the routes have been created **from fundamental research to impact on industry and society**. There are several direct applications resulting from CENS studies (polariscopes based on photoelasticity, interferometer in optics, concepts of marine fairways, software, control algorithms, etc). Clear links between theory and practicalities like piano hammers, short fibres for reinforced concrete, heart cells, nanotubes, light bullets, etc are established.

In other words – the **interdisciplinarity** between several fields in physics and mathematics has created a solid foundation for new results. As mentioned at the IAB meeting (Sept., 2015), the synergy is also related to the fact that CENS provides an **environment** for informal exchange of ideas and concepts, which are beneficial for all the groups. The synergy is possible only due to acting as a whole supported by the existence of CENS and its additional funding as a Centre of Excellence. A matrix of exchange of the ideas between the research fields is shown in the Figure below.

Added value given / Added value obtained	Nonlinear Dynamics	Wave Engi-neering	Optics	Nonlinear Control	System Biology
Non-linear Dynamics		methods, 2D soliton theory	optical wave-beams	control over steer-ing solitons	internal variables in biophysics
Wave Engi-neering	methods, turbulent mixing, 3D images		models of dispersive waves	control over long waves	
Optics	solitons, laser-based tomo-graphy	solitons, wave packets		growth of nanotubes, control of localised waves	spectro-scopy
Non-linear Control	control over wave processes	control in environ-mental processes	control over wave processes		control in real time of single cell
System Biology	thermo-dynamics in physiology, 3D images		optical microscopy	control of cell energetics	

One issue is crucial for all scientific disciplines – **education** of young people. The list of PhD promotions in CENS (see above) is long and many **original university courses** are run by CENS Fellows in the spirit of new knowledge combining basic theories with latest research results. The training of high school students for International Physics Olympiads has been successfully run by a CENS Fellow for almost 20 years. The PhD graduates are working in research as well as in other positions (banking, industrial labs, etc). From the list of graduates shown above, five PhDs work outside Estonia, three – in industry, four continue or have finished their post-doc studies while some are preparing applications for post-doc positions, some teach at the Tallinn UT, etc.

The **capacity of research** has been built up through all the programmes with additional funding and the infrastructure of CENS has been considerably improved. Especial improvement is evident for the laboratories of systems biology, visualization, photoelasticity, and optics which have all excellent experimental facilities (see Laboratory Basis) while wave engineering uses "natural laboratories" – sea and coast for experiments. New equipment has been extensively used. The CENS library at the Institute of Cybernetics has the best collection of books in Estonia on nonlinear science (solitons, fractals, waves) and complexity.

Another important issue is the **internationality of research**. There are many nationalities working in CENS as permanent Fellows or studying for their PhD degree. Permanently are working in CENS R. Birkedal Nielsen (Denmark), H. Herrmann (Germany), T. Torsvik (Norway) who are now leaders of research groups. I. Didenkulova (Russia) was working in CENS until 2015. The contacts with other research centres (see the list) are progressing and many publications expose the results of the joint research by **international teams**.

One should also mention the role of the **International Advisory Board**, who keeps an eye on studies and their valuable comments on Annual Reports have helped to improve the performance of CENS.

Last but not least – CENS has paid a lot of attention to **popularisation of science**. Thanks to numerous articles in popular science magazines, lectures and classes, the Estonian society is informed what is nonlinearity, what is complexity, and what all that is about. Hopefully this has changed mindset at least in some parts of the society although we know that there is a long way to go.

The research will go on because there are many unanswered questions and **new challenges** in wave dynamics, bioenergetics, optics, microstructured materials, turbulence, etc – all entwined into complexity canvas. This area, as described above, is wide and needs future studies. The creative environment for research and young people support the perspectives in the future.

SUMMA SUMMARUM

UNDERSTANDING, MODELLING AND CONTROL OF COMPLEX DYNAMICAL PROCESSES:

INFLUENCE OF NONLINEARITIES AND DYNAMICAL INTERACTIONS

ROLE OF DISPERSION AND DIFFUSION

EMERGENT PATTERNS AND COHERENCE

CONTINUOUS- AND DISCRETE-TIME SYSTEMS

ANALYTICS, NUMERICS, AND EXPERIMENTS

TEACHING AND DISSEMINATING OF KNOWLEDGE

OPINIONS FROM THE IAB

Based on the IAB meeting and the CENS conference on 13-14 September 2015 (Tallinn), the IAB concluded (summary from various opinions of IAB members).

PRELIMINARIES

In order to survive in a harsh international competition and, if possible, renew its objective and expand in a controlled manner, a scientific research structure of excellence such as the CENS must apply certain working rules and comply with some obligations. Among these we emphasize:

- Some rules dictated by the relative smallness of the structure in a small country must be obeyed. These include a focus on a selection of subject matters that will together contribute to a clear vision of a rather precise scientific field. The latter may have grown along different branches but still keeping a common kernel with a marked originality that is clearly identified by external observers. Diversification and introduction of new subjects of interest must be achieved appropriately but with some control.
- An intense network of co-operations with other institutions in various countries is needed so as to avoid any risk of isolation and to favour creative innovations.
- A renewal of leadership is needed. This requires an active formation policy, locally and through exchanges with foreign institutions, as well as with a sufficient flux of newly formed young researchers, including through research stays abroad and long stays of foreign scientists at Tallinn.
- An active international policy of scientific publications eventually complemented by an efficient information of the accomplishments of the CENS to local authorities and the tax payers.

Since its creation the CENS has worked and developed along these lines and successfully followed such obligations.

GENERAL EVALUATION

In spite of its apparent diversity, the Centre has succeeded to keep cohesion and a solid research line that is easily captured by outsiders and is illustrated by a series of well chosen keywords and the very names of the five units that comprise the Centre. Nonlinearity and complexity certainly are the two words that best encapsulate all of its activity. The notions of dynamics and processes are also well adapted to characterize this activity. As for what concerns more especially precise fields of research, the CENS remains marked by its origin, where waves, informatics and engineering were the main contributing elements.

The Centre for Nonlinear Studies successfully completed its work in 2015. All contributing research groups obtained first class results of fundamental importance as well as practical impact. Some groups are among the scientific leaders internationally in the field of nonlinear systems. In their essential parts, the studied topics address the structure and dynamics of nonlinear dynamic processes in natural and artificial systems. The universality of the mathematical laws in the relevant mechanisms was clearly demonstrated. In particular, the results cover nonlinear wave phenomena in structured solids, ocean scenarios, complex biological molecular structures, and structured broadband optical waves and wave-packets. Furthermore, basic mathematical investigations in control theory were presented. The analytical and numerical mathematical tools represent a high standard. Selected topics like ocean dynamics in the Baltic Sea, heart medical studies or glass photoelasticity, to give only a few examples, are obviously of significant potential economic impact. On a fundamental level, the intriguing analogies between many kinds of wave and complexity effects might be of general interest. They open not only perspectives for novel engineering solutions but insight into the working principles of nature as well.

In some way we should apply the theory of complex systems to the Centre itself. The Centre produces an outcome that is greater than the sum of the parts - the parts here being the individual researchers who could act on their own but see the benefit of mutual activities and promote the sharing of best practice.

SPECIFIC REMARKS ON SOME FIELDS OF RESEARCH

Wave Engineering

The focus is on water waves in shallow water impacting on the coast. By using data specific to Estonian coast and the Baltic Sea, this group has developed seminal concepts about modelling wave impacts on beaches. Significantly it has benefited from close international collaborations. It is a high priority that this area be enabled to continue and grow further as a world-leading research group.

Systems Biology

The group is studying the regulation of intracellular processes and understanding the influence of intracellular interaction. Research is based on experimental analysis, (bio)physical modelling and computational analysis. Two more recent highlights are here briefly mentioned: (i) kinetic measurements on the role of the enzyme Na+/K+/-ATPase;(ii) the mechanism of the diffusion restriction at the mitochondrial outer membrane level. Results are published in high-impact journals and the Head of the Laboratory was able to carry in about 1 Meuro grant from the Wellcome Trust (2007-2014).

Nonlinear Dynamics

The studies on nonlinear waves in solids with the focus on the effect of microstructure are internationally competitive and seminal complemented by original viewpoints on some thermodynamic approach and development in modern techniques of acousto-diagnostics. It is worth mentioning the research in the Laboratory of Photoelasticity with the spin-off company GlasStress AP, running also Summer Schools in Tallinn, UK and the US.

Nonlinear Control Theory

The research is at the forefront of international research and combines important new developments on nonlinear control theory with software implementation that allows an application of those results – a rare, noteworthy and admirable combination.

Optics

The group performed fundamental research at the very front of ultrashort-pulse wave optics. As it was demonstrated by the group, the formation and transfer of images by truncated Bessel-like beams can be realized. Another important topic of practical relevance was the temporal focusing of ultra-broadband light which can be applied to explore processes in nature with unprecedented temporal resolution. Remarkable results with respect to laterally non-dispersing Airy bullets open new prospects for sophisticated applications in photonics and optoelectronics which require curvilinear propagation characteristics.

TEACHING AND POPULARISATION

The distribution of PhD students does not have to be uniform in the units, but the change in the interest of the young research generation may lead to required changes in the structure of the centre, too. With appropriate tenure-track system, the next generation of applicants can be steered at a certain level, but the human resources of the centre could also be varied accordingly in the future.

The gained knowledge is also connected with teaching so that students and young scientists achieve the latest output from this Centre. Very impressive is also the successful effort to communicate research results to the society by means of, e.g., a book (in Estonian language) with the title "Keeruka maailma võlu" compiled by the Estonian science writer Tiit Kändler. It is an educational book which explains scientific findings of CENS in a language written for the public – even equations are illustrated for understanding by high school pupils. This is an example which should be followed by other groups and other countries.

In different levels, both the units alone and the whole centre together made serious and successful efforts to make their scientific results not just for the international research community, but also for the non-expert decision makers and tax-payers of their country. Some traditional work like the preparation of students for Physics Olympiads had always been there in the work of the centre, but the last 5 years show a significant improvement in popularization.

GENERAL RECOMMENDATIONS

It is recommended continuing the activities of the Centre. Studies in nonlinear wave propagation, which is a central element in many applications, and also studies in systems biology need surely be supported. In future work, particular emphasis should be laid on strongly focusing on a rather limited number of research topics of highest excellence on the basis of previous results. It might be that some consideration could be given to forming several groups along the topics of Nonlinear Dynamics.

Among the new noticeable strengths we note the proposal of moving fractal sets and associated scaling laws, the explicit presentation of a general mechanism of single-cell bioenergetics, the method of integrated nonlinear photo-elastic tomography, and the all round approach to waves at sea, wave climatology, pollution, and coastal protection. Many of these subjects are not only truly scientific but they also strongly contribute to socio-economical pre-occupations. The field of optics further extends to measuring techniques, plasmons on surfaces and other areas of interest where one has to expect strong synergetic effects and the design of technical devices. In particular CENS has a unique selling point in that engineers and applied mathematicians are brought together with a wide view on the field ranging from important research in control theory to more applied topics around sea waves. The Centre can (beside research) provide an environment for informal exchange of ideas and concepts which are beneficial but often not actually realized in actual publication-producing collaborations.

PROPOSAL

The emphasized change in the concept of "excellence centre" should necessarily pose questions that need serious pondering. One that may sound marginal is the possible change of name of the Institute. Although historical, the "cybernetics" in its title still puzzles many external observers. It would be better to give it a name such as the "Alumäe Institute of Nonlinear and Complex Sciences" that will be more exact from the scientific viewpoint while earn marking the "Estonian" nature with the name of an eminent Estonian scientist. This may trigger some new developments.

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