University of Groningen

Faculty of Mathematics and Natural Sciences

Research Institute of Mathematics and Computing Science

Annual Report 2004
Introduction

Some statistics

In 2004 the institute comprised 23 tenured scientific staff members and six support staff members. Some 50 PhD candidates were enrolled, including 19 Ubbo Emmius scholarships for students from abroad, 12 PhD positions funded by the Netherlands Organisation for Scientific Research (NWO) and nine PhD positions funded by the European Union, industry or other external funding. Ten postdocs worked at the institute of whom two funded by NWO and one by the Royal Dutch Academy of Sciences, KNAW.

Ten doctoral dissertations were successfully defended.

A total of 102 journal papers, three edited books, three contributions to books, 46 refereed contributions to conference proceedings and 25 other professional publications were published.

Members of the institute served as editors-in-chief, associated editors or members of the editorial boards of 10 international journals and book series.

The institute was visited by 41 foreign scientists.

Personalia

In April J. Willems, head of the research group Systems and Control from 1973 until 2003 and who retired in 2003, was decorated as "Companion of the Order of the Dutch Lion" (a royal decoration) for his fundamental contributions and his leadership in the area of Systems and Control.

In January R. Jansen received a VICI-grant from the Netherlands Organisation for Scientific Research (NWO) for his research programme "Bioinformatics for unravelling complex biological systems". The VICI-grant is a grant for experienced researchers, who have successfully demonstrated that they can develop their own innovative line of research, to further stimulate their development. Jansen received kE 1.250 (kE 845 from NWO and kE 405 from the University of Groningen). In September the research group Bioinformatics left the institute and moved to the Groningen Biomolecular Sciences and Biotechnology Institute in Haren, one of the three institutes of Biology of the Faculty of Mathematics and Natural Sciences.
At the end of the year *J. Bosch* (head of the research group Software Engineering) moved to Finland to become head of the Software and Application Technologies Lab of the Nokia Research Center in Helsinki. In December *D. Hammer* became head (ad interim) of the research group Software Engineering.

Prof.dr.sc.techn. N. Petkov  
Scientific Director

Prof.dr. W.C. Nieuwpoort  
Chairman of the Advisory Council
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**Governing body and support staff**

**Scientific director**  
Prof.dr.sc.techn. N. Petkov

**Advisory counsel**  
Prof.dr. W.C. Nieuwpoort – chairman  
(emeritus, professor of theoretical chemistry, RUG)  
Prof.dr. R.F. Curtain  
(professor of mathematics, RUG)  
Prof.dr. G.R. Renardel de Lavalette  
(professor of computing science, RUG)  
Prof.dr. H.A. van der Vorst  
(professor of mathematics, University of Utrecht)

**Management team**  
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<tr>
<td>Prof.dr.sc.techn. N. Petkov (director)</td>
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<tr>
<td>Dr. Y.E.F.M. Jeuken (scientific policy collaborator)</td>
<td>0.5</td>
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<tr>
<td>J. de Jong-Schlukebir (controller)</td>
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<tr>
<td>A. Navest (controller)</td>
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**Technical and administrative staff**

**Technicians**  
P.C. Arendz 0.5  
H. Paas 0.5  
J. Bokma 0.5

**Secretaries**  
E.D. Elshof 0.35  
D.J. Hansen 0.8  
Y.G.M. Vergnes 0.8

**Secretary of Research Institute**  
H. Steenhuis 0.7
Address:

Post:
P.O. Box 800
9700 AV Groningen

Visitors:
Blauwborgje 3
9747 AC Groningen
The Netherlands

Tel    : 050-3633973
Fax    : 050-3633800
email: research@cs.rug.nl, research@math.rug.nl

List of scientific programmes and tenured scientific staff

Mathematics

Programme 1 : Algebra and Geometry  
Prof.dr. M. van der Put  
Dr. J. Top  

Programme 2 : Analysis  
Prof.dr.ir. A. Dijksma (till 01-03-2004)  
Prof.dr. E.G.F. Thomas (till 01-03-2004)  

Programme 3 : Dynamical Systems & Analysis  
Prof.dr. H.W. Broer  
Dr. M. Martens  
Prof.dr.ir. H.S.V. de Snoo  

Programme 4 : Systems and Control  
Prof.dr. R.F. Curtain  
Prof.dr.ir. A. Dijksma (since 01-03-2004)  
Dr. H. Glüsing-Lürssen (since 01-09-2004)  
Prof.dr. H.L. Trentelman  

Programme 5 : Probability and Statistics  

Programme 6 : Computational Mechanics and Numerical Mathematics  
Dr. K.W.A. Lust (since 16-08-2004)  
Prof.dr. A.E.P. Veldman  
Dr.ir. R.W.C.P. Verstappen  
Dr.ir. F.W. Wubs
Computing Science

Programme 7: Software Engineering  
Prof.dr.ir. J. Bosch  
Dr.ir. J.A.G. Nijhuis

Programme 8: Fundamental Computing Science  
Prof.dr. W.H. Hesselink  
Prof.dr. G.R. Renardel de Lavalette

Programme 9: Intelligent Systems  
Dr. M. Biehl  
Prof.dr.sc.techn. N. Petkov  
Dr. M.H.F. Wilkinson

Programme 10: Scientific Visualization and Computer Graphics  
Dr. H. Bekker  
Prof.dr. J.B.T.M. Roerdink  
Dr. G. Vegter

Programme 11: BioInformatics  
Prof.dr. R.C. Jansen
Research schools

Researchers of the IWI participate in the following research schools:

1. **Mathematical Research Institute (MRI)**
   - Coordinating institution: University of Nijmegen
   - Director: Prof.dr. J.H.M. Steenbrink
   - Participating IWI programme(s): 1, 2, 3, 5

2. **Dutch Institute of Systems and Control (DISC)**
   - Coordinating institution: Delft University of Technology
   - Director: Prof.ir. O. Bosgra
   - Participating IWI programme(s): 4

3. **The J.M. Burgers Centre for Fluid Dynamics**
   - Coordinating institution: Delft University of Technology
   - Director: Prof.dr.ir. G. Ooms
   - Participating IWI programme(s): 6

4. **Dutch Graduate School in Logic (LOGICA)**
   - Coordinating institution: University of Amsterdam
   - Director: Prof.dr. D.J.N. van Eijck
   - Participating IWI programme(s): 8

5. **Institute for Programming Research and Algorithmics (IPA)**
   - Coordinating institution: University of Eindhoven
   - Director: Prof.dr. J.C.M. Baeten
   - Participating IWI programme(s): 8

6. **Advanced School of Computing and Imaging (ASCI)**
   - Coordinating institution: Delft University of Technology
   - Director: Prof.dr. A.S. Tanenbaum (Free Univ. Amsterdam)
   - Participating IWI programme(s): 9, 10

7. **School of Behavioral and Cognitive Neurosciences (BCN)**
   - Coordinating institution: University of Groningen
   - Director: Prof.dr. G.J. ter Horst
   - Participating IWI programme(s): 9, 10
1. **Algebra and Geometry**

**Group leader:** Prof.dr. M. van der Put

### Tenured staff (IWI members)

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<tr>
<td>Prof.dr. M. van der Put</td>
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<tr>
<td>Dr. J. Top</td>
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### PhD students

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<tr>
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<td>R. Carls</td>
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<tr>
<td>R.N. Kloosterman</td>
<td>RuG-NWO</td>
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<tr>
<td>L. Taelman</td>
<td>NWO</td>
<td>1.0</td>
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<tr>
<td>I. Polo Blanco</td>
<td>RuG-UE</td>
<td>1.0</td>
</tr>
<tr>
<td>S. Meagher (since 1-10-2004)</td>
<td>RuG</td>
<td>1.0</td>
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<tr>
<td>Nguyen An Khuong (since 1-11-2004)</td>
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### Guests

- J. Gonzalez Gonzalez, PhD student, Bilbao, Spain
- Prof.dr. M. van Hoeij, University of Florida, USA
- Prof.dr. F. Ulmer, University of Rennes, France
- Dr. Y.A. Amrane, University of Caen, France
- Dr. R. Gerkmann, University of Erlangen, Germany
- Dr. T. Dokchitser, University of Durham, England
- Dr. J.A. Weil, University of Limoges, France
- Prof.dr. J-F. Mestre, University of Paris-7, France
- Prof.dr. G. Frey, University of Essen, France
- L. van der Zalm, Hogeschool Leeuwarden, The Netherlands
1.1 Research Program

1. *Number theory and Algebraic geometry.* Arithmetic properties of elliptic curves over a number field or a function field, like the rank of the Mordell-Weil group, the conductor, associated Galois representations, are the subject of study. Also work is done on applications to Diophantine equations, coding theory and arithmetic algebraic geometry.

2. *Ordinary differential equations.* This concerns algebraic, analytic (e.g., multisummability) and algorithmic aspects of linear differential and linear difference equations; differential Galois theory and its applications, in particular to symbolic (algorithmic) solvability of equations; (Lie) symmetries of nonlinear differential equations.

3. *Rigid analytic geometry.* In particular: Abhyankar’s conjecture, Mumford curves and applications to arithmetic algebraic geometry.

4. *Drinfeld modules.* This concerns a theory in positive characteristic which has similarities with the theory of elliptic curves and Abelian varieties.

1.2 Overview of scientific results

*ad* (1) A joint paper by Top, E.W. Howe (Center for Communications Research, San Diego) and K.E. Lauter (Microsoft Research, Redmond) on curves without any points over finite fields was written. The paper will become a chapter in a book on Arithmetic Geometry and Coding Theory edited by Y. Aubry and published by the Société Mathématiques de France.

Kloosterman’s results on Shafarevich groups of elliptic curves where accepted for publication in the Séminaire de Th. des Nombres in Bordeaux.

Kloosterman in joint work with O. Tommasi (Nijmegen) solved a problem on cubic curves posed by E. Mezzetti (Trieste) and was able to generalize the solution to curves of arbitrary degree. A joint paper on this is accepted for publication in Indagationes Mathematicae.

Kloosterman completed research on moduli of elliptic surfaces; especially, the problem of estimating the dimension of the locus of surfaces with given Picard number. A paper on this was written and submitted for publication in the Journal of Differential Geometry.
Kloosterman studied the group of sections and the possible structures as elliptic surface on certain classes of elliptic surfaces. Three preprints on this are now used as chapters in his forthcoming PhD thesis and will be submitted in the near future.

Kloosterman and Polo studied real cubic surfaces, especially the problem of realizing these as blow-ups of the real projective plane. They found examples where such a realization does not exist; a paper on this is in preparation.

Polo continued her investigations concerning the plaster models of surfaces which are present at several mathematical institutes. Assisted by Lotte van der Zalm, a student from the Hogeschool Leeuwarden, this led to a complete inventory of the models in Groningen. A webpage containing the results of this inventory is in preparation.

Polo wrote, based on her master’s thesis, a paper on the mathematics of Alicia Boole and her connections with Groningen university (especially with P.H. Schoute).

Top finished his collaboration with L.N.M. van Geemen (Milano) on arithmetic properties of certain $K3$-surfaces. A paper on this was accepted for publication in the Bulletin of the London Mathematical Society.

Top’s paper with N. Yui on equations of certain semi-stable extremal elliptic surfaces was accepted for publication in Rocky Mountain Journal of Mathematics.

Carls finished his PhD work extending the theory of Satoh and Mestre on the construction of canonical lifts of abelian varieties. As an application, this gives very efficient algorithms for counting the number of points on curves and on abelian varieties over finite fields. In November, Carls obtained his PhD-degree for these results.

*ad* (2) Joint work with F. Loray (Rennes) and F. Recher(Lille) resulted in a paper on foliations, published in “Publications Matemàtiques”.

Cooperation between M. Berkenbosch, M. van Hoeij and J.-A. Weil (University of Nice) resulted in a chapter of the PhD-thesis of Berkenbosch. This, together with his results on moduli spaces of linear differential equations and in particular on the locus of equations with given Galois group, formed his PhD-thesis which he successfully defended in November.

*ad* (3) A “revised and expanded second edition” of the book *Rigid analytic spaces and applications*, written by Van der Put in collaboration with J. Fresnel (Toulouse),
appeared in the Progress in Mathematics series of Birkhäuser-Verlag.

H.H. Voskuil and M. van der Put published a paper on “Discontinuous subgroups of $\text{PGL}_2(K)$” in the Journal of Algebra.

*ad (4) Van der Heiden published several papers on Drinfeld modules and their applications: an application of Drinfeld modules to factorisation algorithms for polynomials appeared in Mathematics of Computation; a local/global result appeared in the Journal of Number Theory; a construction of a Weil pairing for Drinfeld modules appeared in the Monatshefte für Mathematik; A paper which applies the Weil pairing to compactification problems is submitted for publication in the Journal of Algebra.

Taelman’s paper on properties and applications of Dieudonné-determinants to $t$-motives and to systems of differential equations was accepted for publication.

Top’s collaboration with Chad Schoen on applications of the Drinfeld reciprocity laws from this theory to algebraic geometry resulted in a manuscript which is supposed to be completed in 2005.

### 1.3 Research subjects

**M. Berkenbosch:** algebraic aspects of differential equations, especially moduli problems.

**R. Carls:** counting rational points on curves and abelian varieties over finite fields.

**Nguyen An Khuong:** algebraic aspects of differential equations.

**R. Kloosterman:** arithmetic algebraic geometry, especially Selmer groups and elliptic curves and surfaces.

**S. Meagher:** curves over finite fields.

**M. van der Put:** rigid analytic geometry, Drinfeld modules, differential equations, difference equations, computer algebra.

**L. Taelman:** moduli of Drinfeld modules.

**J. Top:** arithmetical algebraic geometry in particular: elliptic curves, Galois representations, number theory, Drinfeld modules.

**I. Polo Blanco:** History of mathematics, mathematical models of algebraic surfaces.
1.4 Publications

Dissertations


Books

Contributions to books

Articles in scientific journals


**Other publications**


### 1.5 External funding and collaboration

**External funding**

NWO (2 OIO years). This concerns the Ph.D. positions of Lenny Taelman (4 years, all funded by NWO) and of Remke Kloosterman (1 year of his research project funded by NWO).

**External collaboration**

See 1.2.

### 1.6 Further information

**van der Put:**

Visiting professor at the university of Rennes during the period April 18th until May 16th, 2004; Invited speaker at the conference in honour of J. Fresnel at the university of Bordeaux, June 21–23, 2004; Presented an invited main lecture during the DMV Jahrestagung 2004 in Heidelberg, (13 - 17 September, 2004). Visiting professor at the University of Toulouse during the period December 2004 until July 2005.

**J. Top:**

Was an invited participant at a workshop on Random Matrix Theory at the Isaac
Newton Institute in Cambridge, February 2004; was a speaker at the Vakantiecursus 2004 at the CWI and the TUe; L. Taelman, R. Carls and J. Top participated in a joint seminar with geometers from Leiden university where they presented several lectures:


In June, Top visited the Institut für experimentelle Mathematik in Essen where he presented two lectures. Top was a visiting professor at the Institut Henri Poincaré in Paris during September and October where he presented a course on curves over finite fields; is still editor in chief of the Nieuw Archief voor Wiskunde; was an invited speaker at the algebraic geometry conference in honour of T. Shioda in Tokyo in December; J. Top and B. de Smit (Univ. Leiden)’s book Speeltuin van de wiskunde published by Veen Magazines saw its 4th revised printing in 2004, and in the same year its 5th, 6th and 7th printing.

J. Top and M. van der Put are involved in several European Community projects MEGA, EAGER, GTEM (Galois Theories and Explicit Methods).
2. Analysis

**Group leader:** Prof. dr. E.G.F. Thomas

**Tenured staff (IWI members)**

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<td>Prof. dr. ir. A. Dijksma (till 01-03-2004)</td>
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<tr>
<td>Prof. dr. E.G.F. Thomas</td>
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**PhD students**

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<td>(supervisor: A. Dijksma)</td>
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2.1 Research Program

Professor Dijksma, and Wanjala have in the course of 2004 left the Analysis group to join the Systems Theory group.

_E. Thomas_ continues work on his theory of infinite dimensional distributions with the goal of giving a correct mathematical description of the Feynman ‘path integral’ and related notions.

2.2 Overview of scientific results

_E.G.F. Thomas_

The construction of path integrals (more accurately: path distributions) has turned out to depend on the use of Bernstein’s theorem characterizing Laplace transforms. The intended application of Bernstein’s theorem (and its multidimensional generalization) made an in depth study of the functions of Bernstein class necessary. As a biproduct a new proof was given of the generalized Bernstein theorem, as well as of the Bochner-Schwartz theorem, using the nuclear integral representation theorem.

2.3 Research subjects

_E.G.F. Thomas_: To show, with a view to applications to path distributions, that certain reciprocal polynomials of several variables are functions of Bernstein class and to analyse the resulting measures.

2.4 Publications

_Dissertations_

Articles in scientific journals

3.  *Dynamical Systems & Analysis*

**Group leader:** Prof.dr. H.W. Broer

**Tenured staff (IWI member)**

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<td>Dr.ir. M. Martens</td>
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**Postdocs**

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**PhD students**

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<tr>
<td>I. Gullikers</td>
<td>RuG &amp; NWO</td>
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<tr>
<td>A. Hajra (since 16-04-2004)</td>
<td>NWO</td>
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<td>P. Hazard (since 15-09-2004)</td>
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<td>J. Hoo</td>
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<tr>
<td>O. Lukina (since 1-10-2004)</td>
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<td>Ch.V.V. Mohana Sarma (since 1-11-2004)</td>
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<td>K. Saleh</td>
<td>KNAW</td>
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<td>E.N. Subramanian</td>
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Visitor
M. Wojtylak, Krakow, Poland

Guests
Prof. Dr. C. Liverani, Un. Roma, Italy
Prof. Dr. M. Lyubich, Toronto, Canada
Prof. Dr. W. de Melo, IMPA Rio de Janeiro, Brazil
Prof. Dr. M. Peixoto, IMPA Rio de Janeiro, Brazil
Dr. H. Hanßmann, RWTH Aachen, Germany
Dr. F.O.O. Wagener, Universiteit van Amsterdam
Dr. M.C. Ciocci, Rijksuniversiteit Gent, Belgium
Dr. A. Fleige, Dortmund, Germany
Prof. Dr. F.H. Szafraniec, Krakow, Poland
Prof. Dr. H. Woracek, Wien, Austria
Prof. Dr. S. Hassi, Vaasa, Finland
Prof. Dr. M. Möller, Johannesburg, South Africa
Prof. Dr. Yu. M. Arlinskii, Lugansk, Ukraine
Prof. Dr. V.A. Derkach, Donetsk, Ukraine
Prof. Dr. Z. Sebestyén, Budapest, Hungary
3.1 Research program

The research programs Dynamical Systems and Analysis have a solid common basis, well founded in Mathematical Physics. The connecting elements are ordinary differential equations, or in general evolution equations. One specific common interest consists of the spectral theory of Schrödinger operators.

3.1.1 Dynamical Systems

The discipline of Dynamical Systems is concerned with mathematical models for deterministic time evolutions. A simple example is derived from the oscillator, which generally only displays periodic dynamics. If subject to periodic driving or to coupling with another oscillator, it can illustrate many parts of the Dynamical Systems research program.

One possible state of the system is resonance, where the combined system assumes one globally periodic state, the frequency of which is an integer combination of the individual periodic motions. Another possible state is multi- or quasi-periodicity, where the individual periodic motions combine in a rationally independent way. When coupling three oscillators, a third possible combined state exists, where a continuous range of frequencies is present: this is the state of chaos.

The occurrence of resonance, quasi-periodicity and chaos as well as the transitions or bifurcations in between, is the central theme of research in the current Dynamical Systems program – not only for a few coupled oscillators but for a wide class of systems.

The questions posed vary from fundamental to applied, where the focus can be on different classes of systems. Examples of this are the world of general ‘dissipative’ systems with a finite dimensional state space, the classes of Hamiltonian or reversible systems or systems with a very low dimensional state space. Also concrete examples are sometimes studied, where sometimes numerical or symbolic algorithms have to be developed. The mathematics of these different levels strongly interact. For instance, in order to know what to look for in a special case, one has to know what can be expected and what is logically possible.

There is cooperation with groups in other sciences on the analysis of specific systems. This concerns the Physics Department, VU Amsterdam (D. Lenstra and B. Krauskopf), the Department of Engineering, University of Bristol as well as the KNMI and the University of Utrecht (O. Diekmann, T. Opsteegh, F. Verhulst). Var-
ious PhD students and postdocs of all these institutions are involved as well. The theoretical work is internationally oriented and involves intensive cooperation with a.o. the universities of Dijon (R. Roussarie), Houston (M. Golubitsky), Barcelona (C. Simó and À. Jorba), Ghent (A. Vanderbauwhede), IMPA Rio de Janeiro (J. Palis, W. de Melo, M. Peixoto and M. Viana), the universities of Stony Brook and Toronto (M. Lyubich), the KTH Stockholm (M. Benedicks), the Université de Marseille (S. Troubetzkoy), resulting in joint publications at a regular basis. In part both the fundamental and the more applied research is directed to mathematical physics and also embedded in the FOM-program of the same name; this program funded the PhD student Hoo.

3.1.2 Analysis – Operator Theory

The central theme is the extension theory of symmetric and sectorial operators in Hilbert spaces and in Pontryagin spaces. This extension theory is closely connected to mathematical physics, in particular to explicitly solvable models and singular perturbations. Also there is a connection to system theory, cf. the realization of Herglotz-Nevanlinna functions in terms of transfer functions of conservative systems. Finally we mention the intimate relationship with analysis, in particular with moment problems, interpolation problems, differential operators and canonical systems.

The general framework is an abstract boundary value space for which an analog of Green’s identity holds and which gives rise to a so-called Weyl function (which may be multivalued). The Weyl function itself gives rise to functional models, like reproducing kernel Hilbert or reproducing kernel Pontryagin spaces, but also like abstract conservative systems.

The research in this section is concerned with the development of the general theory and the applications to the above mentioned fields. This is done in collaboration with a large group of mathematicians: Yu.M. Arlinskiǐ (Lugansk), S. Belyi (Troy), V.A. Derkach (Donetsk), A. Fleige (Dortmund), S. Hassi (Vaasa), M. Kaltenbäck (Wien), M.M. Malamud (Donetsk), M. Möller (Johannesburg), Z. Sebestyén (Budapest), F.H. Szafraniec (Krakow), E.R. Tsekanovskii (Niagara), H. Woracek (Wien).
3.2 Overview of scientific results

KAM theory
In KAM theory several projects are running. At the fundamental level there is cooperation of Broer with F. Takens (Groningen, professor emeritus), R.H. Cushman (Utrecht) and F. Fasso (Padova), regarding the persistence of Hamiltonian monodromy under non-integrable perturbations, which has its consequences at the level of semi-classical quantization. A classical problem regarding the unicity of KAM tori also had to be solved. Two papers have been submitted. Concerning the general KAM theory of (isotropic) torus bundles in nearly integrable Hamiltonian systems, research is initiated around the PhD research of Lukina, in cooperation with F. Takens, R.H. Cushman and J.J. Duistermaat (both UU). At the more applied level the group is involved in quasi-periodic bifurcation theory. One ongoing project concerns reversible bifurcations by Broer in cooperation with A. Vanderbauwhede and M.C. Ciocci (Gent) and H. Hanßmann (Aachen). Two papers are in preparation. A related problem area in the Hamiltonian context is centered around the PhD research of Jun Hoo (RUG), where Broer and Hoo, in cooperation with Naudot and Hanßmann (Aachen), just finished three papers.

Bifurcation theory
In cooperation with M. Golubitsky (Houston) and G. Vegter (RUG) the geometry of resonance tongues was investigated in a general (universal) setting. A joint paper with Broer has been published, a second paper with the same authors is in preparation. Another project concerns population predator prey models related to the system of Lotka and Volterra, is centered around the PhD research of Saleh, where Broer, Saleh and Naudot, in cooperation with the mathematicians Krauskopf (Bristol) and Roussarie (Dijon) and the life scientist Poggiale (Marseille), are preparing a joint paper.

Ergodic theory and renormalization in low dimensional systems
Martens is involved in research on decay of correlation in non-uniformly hyperbolic dynamics and to application of universality properties to the ergodic behavior of systems and corresponding bifurcation patterns, in cooperation with M. Lyubich (Stony Brook, Toronto), M. Benedicks (KTH Stockholm) and S. Troubetskoy (Marseille). This research also involves the construction of renormalization fixed points, proving hyperbolicity of the renormalization. This renormalization theory is particularly developed for Hénon like dynamics. Several papers are in prepara-
Algorithms and industrial subjects
At the level of algorithms, Martens is working on scheduling problems and on stochastic behavior of TSP. Also several industrial projects are subject of research, such as print technology, signal processing and matters of security. Here a number of patents were obtained in cooperation with collaborators of the IBM laboratory (New York).

Extension theory
The theory of abstract boundary values and Weyl functions has been carried forward (Derkach, Hassi, Malamud, de Snoo); one paper has been accepted, several others are being prepared. The theory of singular perturbations of selfadjoint operators is being further investigated. Several papers are being prepared (Derkach, Hassi, de Snoo). The decomposition of operators and forms is being studied with S. Hassi, Z. Sebestyén en F.H. Szafraniec. Papers on a nonselfadjoint version of the extension theory of Krein and Ovcarenko and system-theoretic interpretations are being prepared (Arlinskiĭ, Hassi, de Snoo). A paper on normal extensions of symmetric operators is also in preparation (Hassi, de Snoo, Szafraniec). The general representation of matrix valued Nevanlinna functions is being carried forward (Belyi, Hassi, de Snoo, Tsekanovskii) A paper on the general realization result and its system-theoretic interpretation is being submitted. The work on spectral properties of Schrödinger operators with a floating singularity is being continued (Hassi, Möller, de Snoo, Winkler). The representation of not necessarily semi-bounded sesquilinear forms in a Hilbert space remains a research topic (Fleige, Hassi, de Snoo, Winkler); one paper has been submitted, another one is being prepared. The study of nonnegative selfadjoint extensions in the sense of Stochel and Szafraniec is being continued; one paper has been submitted and another is almost finished (Hassi, Sandovici, de Snoo, Winkler). Perturbation of eigenvalues in a gap of a selfadjoint operator is being studied by Hassi, Sandovici, de Snoo, Winkler. An extension to an indefinite setting is done with Wojtyslak. Work concerning strings and reproducing kernel Pontryagin spaces is being continued (Kaltenbäck, Woracek, Winkler). Several papers have been accepted and others are being submitted. Sandovici continued earlier work in differential geometry.

PhD research
Hoo’s PhD research has been completed by the end of the year. It resulted in three preprints, submitted for publication. One paper deals with quasi-periodic bifurcation theory, where the case of multiple eigenvalues in the Floquet matrix, suitable for resonant bifurcations, could be successfully tackled. A second paper applies this
theory to the case of a quasi-periodic Hamiltonian Hopf bifurcation and is applied to the Lagrange top under periodic and quasi-periodic excitation. The third paper gives an overview of all these results.

Saleh is expected to complete his PhD research in 2005. The research is centered around the effect of ‘nearby’ singularities of higher codimension in families of dynamical systems. Also the effects of periodic and quasi-periodic forcing is studied. Partly this study is computer assisted. One joint paper of Saleh with F.O.O. Wagen on a universal model with quasi-periodic forcing, is about to be finished. Another paper of Saleh with Broer, Naudot and B. Krauskopf (Bristol) on a given family of population models related to the Lotka Volterra predator prey system is in preparation, see above.

Subramanian’s research concerns with dynamical systems modelling of the visual neurocortex, especially with large array’s of coupled oscillators. Several problems are under study, e.g., related to synchronization.

The PhD research of Hajra, Hazard, Lukina, Mohanna Sarma and Winckler has started only a few months ago and is yet too early to report on.

Sandovici continued his work on extension theory; a first paper concerning the structure of linear relations will soon appear; several others are being prepared.

3.3 Research subjects

**H.W. Broer:** Perturbation and KAM-theory, bifurcation theory, non-integrable and resonance phenomena, applications of singularity theory, exploration of complicated systems

**I. Gullikers:** Reinvention of geometry.

**A. Hajra:** Computation of a universal four dimensional bifurcation set.

**P. Hazard:** Renormalization of critical circle maps.

**J. Hoo:** Quasi-periodic bifurcations in a strong resonance: combination tones in gyroscopic stabilisation.

**O. Lukina:** Geometry of torus bundles in Hamiltonian systems.

**M. Martens:** Geometry and measure theory of low dimensional dynamics: renormalization and ergodic theory; algorithms and industrial applications.

**V. Naudot:** Bifurcation theory, asymptotic properties of hyperbolic and semi-hyperbolic germs.

**K. Saleh:** Complication of bifurcation diagrams due to nearby degenerate singularities and time dependence.

**A. Sandovici:** Symmetric operators and their selfadjoint extensions.

**Ch.V.V. Mohana Sarma:** Renormalization in low dimensional dynamics: border
cases.

**H.S.V. de Snoo**: Extension and realization theory with their applications to analytical problems.

**E.N. Subramanian**: Dynamical systems modelling of the visual cortex.

**B. Winckler**: Renormalization of Lorenz-flows.

**H. Winkler**: Spectral theory of differential operators and systems in definite and indefinite inner product spaces.

### 3.4 Publications

**Articles in scientific journals**


**Articles in conference proceedings**


**Other publications**


**3.5 External funding and collaboration**

*External funding*

PhD grants (supervisor Broer): Drs. J. Hoo had a FOM grant in the program Mathematical Physics at February 1, 2001; Drs. K. Saleh was appointed on a KNAW PhD-grant at January 1, 2002; A. Hajra had an NWO grant (open competition, co-supervisor G. Vegter) and was appointed April 1, 2004.
PhD Grant (supervisor Martens): Peter Hazard had an NWO grant (open competition) and was appointed September 1, 2004.

H.W. Broer and M. Martens, in collaboration with F. Takens (RuG, professor emeritus) and A.C.D. van Enter (RuG, Theoretical Physics) organized a one-week workshop *Nonlinear Dynamics, Ergodic Theory and Renormalization* at the Lorentz Center of Leiden University (20-24 September 2004). This was a small scale meeting with 70 international experts. The workshop was sponsored externally by NWO, the Dutch national research schools MRI and Stieltjes and the IWI, totally for 16 000 Euro.

H.S.V. de Snoo obtained support from NWO and FOM for the visits of Arlinski˘ı, Derkach and Möller. Visits to Vaasa were supported by the Research Fund of the University of Vaasa.

*External collaboration*

H.W. Broer was involved in external thesis direction and jury membership. In March 2004 he was second promotor at the theological faculty of Groningen University of Taede Smedes, *Avoiding Balaam’s mistake, exploring divine action in an age of scientism*, with L.J. van den Brom as first promotor and A.F. Sanders as co-promotor. In May 2004 he was jury member at the Universitat de Barcelona of Joaquim Puig, *Reducibility of quasi-periodic skew products and the spectrum of Schrödinger operators*, with C. Simó as promotor.

**3.6 Further information**

*Activities by H.W. Broer, M. Martens, V. Naudot 2004*

H.W. Broer, in cooperation with A. Doelman (UvA, CWI) and S.M. Verduyn-Lunel (Leiden), was involved in the development of a national cluster *Nonlinear Dynamics of Natural Systems*, coordinated by NWO. In the proposal Groningen will be the center of this cluster, with Leiden and the CWI as nodes. The activities require infrastructural support by tenured faculty, prefinanced by the ministeries of EZ and OCW, and lateron taken over by center and nodes. Most Dutch researchers in the field of nonlinear dynamics and dynamics of patterns will be involved in the activities, which consist of joint research, coordinated proposals for PhD and post doctoral research and external guests, joint seminars, etc. Also the cluster
will be involved in coordinating input for teaching at the national master and PhD level. A number of these activities have already started, e.g., in the planning for an MRI-Stieltjes Master Class *Finite and infinite dimensional dynamical systems*, organized by Broer, Doelman and S.A. van Gils (UTwente) in 2005-06. The cluster research has a strong focus on life and earth sciences. For Groningen University the NWO coordinated support is foreseen to be at least 1.4 million Euro over four years, starting mid 2005. This budget will serve to prefinance a full professorship and two tenure track positions in Applied Analysis and Dynamical Systems. M. Martens organized a weekly Dynamics Seminar at Groningen University and a more nationally oriented quarterly KAM seminar, occasionally in cooperation with A.J. Homburg (UvA).

**H.W. Broer** gave invited talks at CIRM (Luminy), at the ÉPFL (Lausanne within the RTN European program *MASIE*) and at the Solvay conference at the UB (Brussels). He continued his one month visiting professorship at the Université de Bourgogne (Dijon) where he presented another colloquium talk. He also visited the University of Houston and Boston University for colloquium talks and maintaining joint research. The same holds for the Universitat de Barcelona where he visited twice. Jun Hoo gave an invited talk at the yearly FOM Mathematical Physics meeting, and presented a poster at the Lorentz Center (Leiden). Khairul Saleh also presented a poster at the Lorentz Center.

**M. Martens** gave invited lectures at Orsay, at IMS (Stony Brook), at the KTH (Stockholm), at CIRM (Luminy) and at the International Conference on Dynamics at Trieste. Also he gave general colloquium talks at Utrecht and Groningen Universities and several talks at the Groningen Dynamics Seminar and the KAM seminar. He visited IMPA (Rio de Janeiro), twice at SUNY (Stony Brook), the KTH (Stockholm), and CIRM (Luminy, Marseille).

**V. Naudot** presented a poster at the Lorentz Center (Leiden).

**Activities by A.V. Sandovici, H.S.V. de Snoo, H. Winkler 2004**

Since September 2004 there is a weekly seminar on Operator Theory organized by de Snoo and Winkler; furthermore there is a weekly seminar on Approximation Theory organized by de Snoo and Vegter; the formal lectures are given by Sandovici.

**A.V. Sandovici** gave talks at the 20-th Conference on Operator Theory, June 30 - July 5, 2004, Timisoara, Romania, the 7-th International Conference of Tensor
H.S.V. de Snoo spent 4 weeks in January and two weeks in November at the University of Vaasa. He gave a talk at the TU Vienna Colloquium on Operator Theory (March 4–6, retirement H. Langer), a colloquium lecture at the University of Newcastle (March), a talk at the IWOTA conference in Newcastle (July 12–16), and a lecture at the 4-th Workshop on Operator Theory in Krein Spaces and Applications, December 17-19, 2004, T.U. Berlin.

H. Winkler twice paid longer visits to the T.U. Vienna, and he visited the University of Vaasa, where he also gave lectures. He gave talks at the TU Vienna Colloquium on Operator Theory (March 4–6, retirement H. Langer), Leuven (MTNS, July 5–9), University of Newcastle (IWOTA, July 12–16) and a lecture at the 4-th Workshop on Operator Theory in Krein Spaces and Applications, December 17-19, 2004, T.U. Berlin.
4. **Systems and Control**

**Group leader:** Prof. dr. R.F. Curtain

**Tenured staff (IWI members)**

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<th>Name</th>
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<tr>
<td>Prof. dr. R.F. Curtain</td>
<td>RuG</td>
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<td>Prof. dr. ir. A. Dijksma</td>
<td>RuG</td>
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<tr>
<td>Dr. H. Glüsing-Lürssen (since 01-09-2004)</td>
<td>RuG</td>
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<td>Prof. dr. H.L. Trentelman</td>
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**Postdocs**

Dr. O.V. Iftime (till 31-08-2004)  
RuG  1.0

**PhD students**

H.B. Minh (since 01-11-2004)  
(supervisor: Trentelman)  
RuG-UE  1.0

D.O. Napp Avelli  
(supervisor: Trentelman)  
RuG-UE  1.0

M.R. Opmeer  
(supervisor: Curtain)  
NWO  1.0

G. Schneider (since 01-10-2004)  
(supervisor: H. Glüsing-Lürssen)  
RuG  1.0

F. Tsang (since 01-08-2004)  
(supervisor: H. Glüsing-Lürssen)  
RuG-UE  1.0

G. Wanjala  
(supervisor: Dijksma)  
RuG  1.0

R. Zavala Yoe  
(supervisor: Trentelman)  
RuG-UE  1.0

**Guests**

Prof. D. Alpay, BGU, Beer Sheva, Israel  
Prof. H. Langer, TU, Vienna, Austria  
Prof. C. Tretter, TU, Bremen, Germany  
Prof. T. Azizov, VSU, Voronezh, Russia  
Dr. A. Luger, TU, Vienna, Austria  
Prof. V. Katsnelson, Weizmann Institute, Rehovot, Israel  
Dr. D. Volok, Weizmann Institute, Rehovot, Israel  
Maria del Carmen Perea Marco, Universidad Miguel Hernandez, Elche, Spain  
Maria Victoria Herranz, Universidad Miguel Hernandez, Elche, Spain
Guests (cont.)
Vicente Galiano Ibarra, Universidad Miguel Hernandez, Elche, Spain
Prof. A.J. van der Schaft, UT, Enschede, The Netherlands
Dr. J.W. Polderman, UT, Enschede, The Netherlands
Prof. B. de Moor, University of Leuven, Belgium
Prof. Michael Demetriou, Worcester Polytechnic University, Worcester, USA
4.1 Research Program

The aim of the research in the Systems and Control group is the development of mathematical tools for the modeling of open dynamical systems and of algorithms for their control. There are four lines of research:

- Infinite-dimensional systems theory (Curtain, Iftime and Opmeer)
- Operator theory in spaces with an indefinite metric (Dijksma, Wanjala)
- Algebraic methods in systems and control theory and coding theory (Glüsing-Lürssen, Schneider, Tsang)
- The behavioral approach to systems and control (Trentelman, Minh, Napp Avelli, Zavala Yoe)

4.1.1 Infinite-dimensional systems theory

In many application areas, systems are most accurately described by partial differential equations or delay equations, for example, large scale flexible space structures, noise suppression in large cavities and process control, where there are considerable delays in control implementation. Control problems for such systems can be formulated in an analogous way to those for lumped parameter systems (those described by ordinary differential equations) in state-space form, if one introduces a suitable infinite-dimensional space and suitable operators, instead of the usual matrices. Infinite-dimensional systems theory is concerned with the extension of classic control theory to this more general setting, insofar this is possible. Control design in this context is a synthesis of this theory, taking into account numerical, physical and implementational aspects.

The questions studied for these systems in this project are related to well-posed linear systems, dissipative systems, model reduction and robust control.

Ongoing work

A mathematical formulation of interconnection structures in physical systems (O.V. Iftime, G. Golo, A. van der Schaft, and H. Zwart of Twente University) Most of the current modelling and simulation approaches to physical systems are based on network representation. The physical system under consideration is seen as the
interconnection of a number of systems, possibly from different domains (mechanical, electrical e.a.). We focus on the mathematical description (in Hilbert and Banach spaces) of the interconnection structure.

Suboptimal Hankel norm approximation problem (O.V. Iftime, M.A. Kaashoek of VU Amsterdam and A. Sasane of London School of Economics, UK). Model reduction is an important engineering problem in which one aims to replace an elaborate model by a simpler model without undue loss of accuracy. One way to measure the accuracy is the Hankel norm. We seek to develop a band method approach to solving the suboptimal Hankel norm approximation problem.

Representation of the solutions to Riccati equations (R.F. Curtain, O.V. Iftime, M.R. Opmeer and H.J. Zwart of Twente University) Algebraic Riccati equations may have infinitely many solutions and in finite dimensions these can be represented in terms of invariant subspaces. We have shown that under certain assumptions, this is also the case in infinite dimensions. Work is now done on relaxing the assumptions that the input and output maps are bounded.

Dissipative systems (R.F. Curtain and G. Weiss of Imperial College, London, UK). A large class of flexible structures with collocated actuators and sensors are stabilized by applying static output feedback and the control is usually implemented on the boundary. This can be mathematically formulated as a stabilization problem for well-posed linear systems. Two papers have been submitted on sufficient conditions for exponential stability of the closed-loop system. Presently we are working on sufficient conditions for strong and weak stability.

Reciprocal systems (R.F. Curtain and M.R. Opmeer) The class of well-posed linear systems represents a large class of infinite-dimensional systems that are suitable for modelling a wide variety of control problems for linear partial differential equations and delay equations. A significant problem in applying the theory is that the generating operators are unbounded and so the mathematical analysis is complicated. A novel approach developed by our group is to translate control problems for a well-posed linear system into equivalent control problems for its reciprocal system. Since this system has bounded generators, the equivalent problem for the reciprocal system is more amenable to algebraic and numerical computations. It has proven to be a powerful approach to control design for well-posed linear systems, particular to obtain more general results on the Nehari problem and existence of coprime factorizations for infinite-dimensional systems. In the future we envisage further applications, in particular, to the problem of robust controller design.
LQG balancing and approximation for distributed parameter systems (R.F. Curtain and M.R. Opmeer) Truncations of LQG-balanced realisations provide reduced order models of finite-dimensional systems that are useful in the design of low order controllers. We are developing a theory for the infinite-dimensional counterpart that has been tested numerically by us and by the group of B. King. (Virginia Tech, Blacksburg, Virginia, USA).

Resolvent linear systems (M.R. Opmeer) Not all control systems described by linear partial differential equations are well-posed. We aim for a theory that includes well-posed linear systems and these non well-posed examples. It seems that distributions and the Cayley transform play a key role here.

4.1.2 Operator theory in spaces with an indefinite metric

This theory is an interplay of functional analysis, complex function theory, theoretical physics, systems theory, and electrical engineering and includes the following problems: 1. In quantum mechanics highly singular rank one perturbations of self-adjoint Hilbert space operators occur whose spectral properties one tries to describe using self-adjoint extensions of a symmetric operator in a space with an indefinite metric and corresponding so-called Q-functions, which are in fact generalized Nevanlinna functions. Such functions also appear naturally in the study of the Bessel and Laguerre equations for values of the parameters that have not been considered before. 2. In electrical engineering problems arise which are connected with generalizations of the classical Schur transformation for classical Schur functions to a time varying setting, to a multi-scale setting and also to an indefinite setting. 3. The problem of similarity of a semigroup of contractions on a Krein space to a semigroup of contractions on a Hilbert space comes from the study of uniformly correct Cauchy problems involving certain evolution equations. 4. The spectra of eigenvalue problems involving ordinary and partial differential equations and boundary conditions which contain the eigenvalue parameter can under certain general conditions be studied through linearization to self-adjoint or dissipative operators in Pontryagin spaces.

Ongoing work

Models and singular rank one perturbations (A. Dijksma, P. Kurasov of Lund Institute of Technology, Sweden, H. Langer and A. Luger of the Vienna University
of Technology, Austria, and Yu. Shondin of the Department of Physics, State Pedagogical University, Nizhny Novgorod, Russia) We develop models in terms of self-adjoint operators or relations for generalized Nevanlinna functions with different properties and apply them to highly singular rank one perturbations. We intend to use these models to approximate singular perturbations by means of smoother perturbations and investigate the Bessel operator on the interval (0, 1).

The generalized Schur and Akhiezer transformation (A. Dijksma, G. Wanjala, D. Alpay of the Ben Gurion University of the Negev, Beer Sheva, Israel, T.Ya Azizov of the State University of Voronezh, Russia, and H. Langer of the Vienna University of Technology, Austria) The Schur transformation maps the class of generalized Schur functions into itself and the Akhiezer transformation maps the class of generalized Nevanlinna functions into itself. We study these transformations for their effect on the (co-)isometric and unitary models of generalized Schur and on the self-adjoint models of Nevanlinna functions and for their relation with interpolation of such functions at interior and boundary points of the open unit disc and the open upper half plane, respectively. The results are related to almost orthogonal polynomials and Padé approximation. The transformations can be applied to obtain a factorization of certain classes of rational $2 \times 2$ matrix functions in terms of elementary factors. Most results obtained so far concern scalar functions and we hope to find their matrix analogs.

Spectral problems (A. Dijksma, Y. Agranovich, T.Ya. Azizov, and A. Barsukov of the State University of Voronezh, Russia, P. Jonas and K.-H. Foerster of the TU Berlin, Germany, and H. Langer of the Vienna University of Technology, Austria) The topics here concern invariant subspace problems for operators and semigroups on Krein spaces, spectral properties of block operator matrices with unbounded entries, hyperbolic operator pencils, Cauchy problems, and inverse spectral problems.

4.1.3 Algebraic methods in systems and control theory and coding theory

Coding theory is concerned with reliability of data transmission. When data are sent over a noisy channel, they undergo in general some outside errors and are therefore corrupted when they reach the receiver. Coding theory aims at preprocessing (encoding) the data such that the receiver will be able to recover the correct data from the erroneous ones (decoding). The most widely known tool for this task are block codes. However, since decades engineers also make use of convolutional codes. These codes can, in a certain sense, be regarded as discrete-time dynamical
systems over a finite field. Since the mid 1990’s this insight has led to quite some developments in the mathematical theory of convolutional codes. The research in convolutional coding theory aims at the construction of good codes and at the analysis of the algebraic structure for this class of codes. Besides state-space representations also image and kernel representations of convolutional codes are helpful in this regard. Due to their nature as systems over finite fields this area requires mainly algebraic methods.

**Ongoing work:**

*Cyclic convolutional codes* (H. Glüsing-Lürssen, F. Tsang and W. Schmale, University of Oldenburg, Germany) The concept of cyclicity for convolutional codes has been introduced in the seventies of the last century, but only recently an algebraic theory of cyclic convolutional codes (CCC’s, for short) could be established. It provides both a huge class of powerful codes and a nice generalization of the algebraic theory of cyclic block codes. This research project is concerned with a continuation of the algebraic theory and with an investigation of the class of CCC’s with respect to its coding theoretic properties. This comprises in particular: a detailed study of a certain skew-polynomial ring and the left ideals therein; the existence of CCC’s with arbitrary algebraic parameters (e.g., Forney indices), investigation of certain minimal CCC’s, closely related to a cyclic block code, with respect to distance and decoding properties.

*Weight distribution for convolutional codes* (H. Glüsing-Lürssen, G. Schneider) In this new project it is particularly helpful to interpret a convolutional code as a dynamical system over a finite field. The main tool for computing the weight distribution is the adjacency matrix which is naturally associated with the dynamical system. Due to the non-uniqueness of the ordering of states, the adjacency matrix is well-defined only up to a certain restricted similarity. This matrix will be in the center of the project. It fully determines the classical weight distribution, but actually contains more information about the code. Several questions arise naturally in this area. Is the adjacency matrix an invariant of the code or does it highly depend on the choice of the generator matrix? Is the adjacency matrix invariant under monomial equivalence of convolutional codes? What kind of equivalence on the set of codes is being induced via restricted similarity of adjacency matrices? Is there a MacWilliams identity for adjacency matrices of convolutional codes and their duals?

*Strongly MDS convolutional codes* (H. Glüsing-Lürssen, J. Rosenthal of Univer-
This project aims at the construction of convolutional codes with optimum distance profile. The distance profile is the list of its column distances; they give important information about the decoding capability of the code. In particular, the task requires the construction of certain block Toeplitz matrices with all proper minors being nonzero.

4.1.4 The behavioral approach to systems and control

The basic purpose of systems theory is the study of dynamical systems that interact with their environment. Viewing systems as embedded in their surroundings should be a normal feature of models in physics, engineering and economics, but, in mathematics it is rather uncommon to formalize this interaction. Examples of areas where this aspect is essential are signal processing and control, and it is this last area which is emphasized in our research.

The traditional way of modeling a dynamical system is by an input-output map or relation. However, physical systems in general do not exhibit the information flow direction that is pre-supposed by the input-output structure. This objection has led us to develop the behavioral approach. In this setting, all manifest system variables are a priori treated on an equal footing. The model then specifies a subset of the set in which the manifest variables take their values as being possible. This subset is called the behavior of the system. However, when modeling systems as interconnection of standard components, as is common practice in computer-assisted object-oriented modeling tools, one invariably encounters (auxiliary) latent variables in addition to the manifest variables that the model aims at. Our approach is based on this triptych: manifest variables, behavior and latent variables.

Many questions are studied in this setting. Controllability, pole placement, observability, observers and Lyapunov stability are some classical questions that we are pursuing in this novel framework. Further, state construction and LQ- and H-infinity control. Most of the work aims at linear differential systems.

Ongoing work

systems, quadratic differential forms, Lyapunov theory for systems described by high order differential equations. We start with polynomial matrix representations of a dynamical system (either a kernel or an image representation) and obtain analogous representations of the controller. This problem leads to interesting interactions between polynomial matrices in one and two variables.

Control as interconnection (H.L. Trentelman, R. Zavala Yoe and C. Praagman from the Department of Econometrics, University of Groningen) The purpose of this research project is the formulation of control and representation problems and algorithms in the context of behaviors. The starting point is a set of behavioral equations, for example a system of differential equations \( R \left( \frac{d}{dt} \right) w = 0 \) with \( R \) a polynomial matrix. We view control as interconnection, that is, adding a new system of differential equations \( C \left( \frac{d}{dt} \right) w = 0 \). The resulting closed loop system has been studied w.r.t. stabilization and pole assignment. Also the problem of parametrizing all controllers that implement a given desired controlled behavior is considered.

Modeling and control of distributed systems (D. Napp Avelli and H.L. Trentelman) This program deals with studies on controllability and observability of systems of constant coefficient PDE’s through the behavioral approach. Special emphasis is on the extension of the concept of dissipative distributed parameter systems to the multidimensional case, and on the study of distributed Hamiltonian and variational systems. We aim at developing a behavioral theory of LQ control, H-infinity control and H-infinity filtering for the class of systems described by linear partial differential equations with constant coefficients.

Algorithms in systems and control (H.L. Trentelman and P. Rapisarda from the University of Maastricht, The Netherlands) This project focuses on algorithmic issues in modeling and control. Several algorithmic problems arising in classical systems and control theory can be treated successfully using methods from the behavioral setting. In particular we study the problems of polynomial J-spectral factorization and problems concerning the algebraic Riccati equation.

Stability analysis and robust stabilization of system behaviors via quadratic differential forms (H.L. Trentelman and H.B. Minh). In system engineering it is common practice to use linear, time-invariant plant models. For this class of models there exists a well-established theory. In particular, in the 1960-70’s a large body of results was developed, often referred to as ‘absolute stability theory’. Recently, Rantzer and Megretski have put the existing theory into a unified framework by using the concept of integral quadratic constraint (IQC). In this research project
we aim at extending the existing theory on IQC’s by putting it in a more general framework of behavioral systems.

4.2 Overview of scientific results

4.2.1 Infinite-dimensional systems theory

Progress has been made in all the research projects listed above.

*Absolute stability and integral control* This project from 2003 has now been finalized with the publication in 2004 of the last of a sequence of 3 papers.

*Dissipative systems* Two papers have been submitted on sufficient conditions for exponential stability of the closed-loop system.

*Reciprocal systems* The novel idea of reciprocal systems has proven to be a very successful and fruitful approach. One paper on Riccati equations appeared in SCL this year and two new journal papers have been submitted. These three papers represent significant generalizations of classic system theory results to larger classes of infinite-dimensional systems. See also the CDC paper on robustly stabilizing compensators.

*Resolvent linear systems* A paper on resolvent linear systems has been submitted.

*LQG balancing for infinite-dimensional systems* A paper on the existence of LQG balanced realizations for the discrete-time case appeared in SIAM journal on control and optimization this year.

*Representation of the solutions to Riccati equations* A paper on the representation of all self-adjoint solutions of Riccati equations is under review and some extensions to unbounded operators was presented at the CDC.

*Suboptimal Hankel norm approximation problem* A paper on the suboptimal Hankel norm approximation problem has appeared in Systems and control letters and one has been presented at the MTNS.
4.2.2 Operator theory in spaces with an indefinite metric

In each of the three topics mentioned new results have been obtained.

Models and singular rank one perturbations: A. Dijksma, H. Langer, A. Luger, and Yu. Shondin have constructed a self-adjoint operator/relation model for a generalized Nevanlinna function which corresponds to its basic factorization as a product of a rational function and a Nevanlinna function. A. Dijksma, H. Langer and Yu. Shondin classified all generalized Nevanlinna functions which have only one pole, namely at infinity, and this pole is not of positive type. These functions arise in singular perturbations and are related to the notion of infinite coupling. Together with A. Luger they developed a model for such functions. In a recently accepted paper A. Dijksma, P. Kurasov, and Yu. Shondin compare two approaches to singular rank one perturbation of a positive self-adjoint operator in a Hilbert space, one approach using an operator model in a Hilbert space and the other one (with a longer history) using an operator model in a Pontryagin space.

The generalized Schur and Akhiezer transformation: As part of his Ph.D project G. Wanjala has investigated topics around the Schur transform. Jointly with D. Alpay, T.Ya. Azizov, A. Dijksma, and H. Langer, he published a paper on the effect of the Schur transform on the unitary model for generalized Schur functions. He describes similar results in a recently accepted paper by using reproducing kernel methods. Under review is a paper by A. Dijksma and G. Wanjala in which the well known Schur parameters are generalized to an indefinite setting. The so-called augmented Schur parameters uniquely determine the function they are constructed from. Finally, A. Dijksma, D. Alpay, and H. Langer showed that factorization of $2 \times 2$ matrix polynomials which are $J$-unitary on the circle into elementary factors has a counterpart to factorization of $2 \times 2$ matrix polynomials which are $J$-unitary on the line.

Spectral problems: T.Ya. Azizov, A. Barsukov, and A. Dijksma obtained necessary and sufficient conditions under which a $C_0$-semigroup of bi-contractions on a Krein space is similar to a semigroup of contractions on a Hilbert space. Under these and additional conditions they found direct sum decompositions of the space into invariant regular subspaces and they described the behavior of the semigroup on each of this subspaces. In another paper they solved a Cauchy problem in which the main (unbounded) operator is dissipative in a certain indefinite metric and such that its domain contains a subspace which is maximal uniformly negative relative to this metric. Jointly with Y. Agranovich they solved an inverse problem for a quadratic pencil with Jacobi matrix coefficients.
4.2.3 Algebraic methods in systems and control theory and coding theory

In all three projects progress has been made.

*Cyclic convolutional codes:* A paper with the algebraic theory of cyclic convolutional codes has appeared and another paper about the construction of codes with prescribed algebraic parameters has been accepted for publication. Two more papers on constructions of (cyclic) convolutional codes with large distance have been submitted. In one of these papers one-dimensional MDS convolutional codes are constructed and investigated with respect to cyclicity. Thus, these codes are optimal with respect to their free distance among all codes with the same algebraic parameters. In the other paper we construct a class of Reed-Solomon convolutional codes. We can compute the distance of these codes and they turn out to be quite good and even optimal for small dimension. These papers indicate that cyclic structure for convolutional codes is beneficial for the analysis of these codes.

*Weight distribution for convolutional codes:* This project has just been started. Currently a paper is in preparation where it is shown that the adjacency matrix can be regarded as an invariant of the convolutional code. Moreover, it is shown that for binary one-dimensional codes the adjacency matrix even forms a complete invariant of the codes under monomial equivalence. We believe that this result can be generalized to one-dimensional codes over arbitrary fields.

*Strongly MDS convolutional codes:* A paper is currently under review. Therein we prove the existence of strongly MDS convolutional codes for quite some classes of parameters. We also use our methods to discuss the extended row distances of strongly MDS unit memory codes and can prove that these distance parameters are bounded from below by a linear function with large slope. This is important information concerning the decoding capabilities of these codes.

4.2.4 The behavioral approach to systems and control

The main emphasis in the research concerned with the behavioral approach to systems and control during 2004 has been on the following related topics:

- Control as interconnection
- Synthesis of dissipative systems
- Systems described by PDE’s
Behavioral systems

Within the project on control as interconnection there has been much progress. In a paper that was accepted for publication in the Proceedings of the 16th IFAC World Congress in 2005, we have developed algorithms to resolve the so-called unimodular and stable embedding problems. The first problem deals with extending a given polynomial matrix to a square matrix such that the resulting polynomial matrix is unimodular, the second deals with extending it to a Hurwitz matrix.

In a second paper that was accepted for publication in the Proceedings of the IFAC World Congress in 2005, we have solved the problem of parametrizing all behavioral controllers that regularly implement a given desired subbehavior of the plant behavior by full interconnection. This result has been applied to establish a (Youla like) parametrization of all behavioral controllers that stabilize a given plant, thus generalizing a well known results M. Kuijper. More recently we have succeeded in establishing parametrizations for the general case of partial interconnection.

In the context of synthesis of dissipative systems some results have been obtained on the computation of behavioral controllers that make a given plant behavior dissipative with respect to a given supply rate. These algorithms are based on ideas around J-spectral factorization algorithms using Pick matrices. Also, the problem of synthesis of strictly dissipative systems was resolved in a joint paper with M.N. Belur that appeared in Systems and Control Letters in 2004.

Within the project on systems described by PDE’s, in 2004 a long paper on linear Hamiltonian behaviors has appeared in the SIAM Journal on Control and Optimization. In addition, some preliminary results have been obtained on the behavioral version of the LQ optimal control problem for nD-systems.

In the context of general behavioral systems, in 2004 a paper has appeared in Systems and Control Letters on flatness of systems. A flat system is a system for which there exists a mapping such that the manifest system behavior is equal to the image of this mapping, and such that the latent variable appearing in this image representation can be written as a function of the manifest variable and its derivatives up to some order. For linear differential systems, flatness is equivalent to controllability. We have generalized the main theorem of a paper by J. Levine to general linear differential systems.
4.3 Research subjects

**R.F. Curtain:** LQG-balanced realisations and truncations for distributed parameter systems with applications to robust control design, reciprocal systems for well-posed linear systems, spectral factorization problems for nonrational transfer functions, Riccati equations for infinite-dimensional systems, normalized coprime factorizations for well-posed linear systems.

**A. Dijksma:** the generalized Schur and Akhiezer transform for generalized Schur and generalized Nevanlinna functions and time-varying analogs with applications to interpolation and factorization, singular rank one perturbations in mathematical physics, and inverse spectral problems

**H. Glüsing-Lürrsen:** construction of convolutional codes with large distance, cyclic convolutional codes, weight distribution of convolutional codes.

**O.V. Iftime:** Riccati equations for infinite-dimensional systems, $J$-spectral factorization in frequency domain with applications to control problems, Port-Based Models: Interconnection Structures.

**H.B. Minh:** Stability analysis and robust stabilization of system behaviors via quadratic differential forms


**M.R. Opmeer:** LQG-balancing and truncations for distributed parameter systems with applications to robust control design, reciprocal and discrete-time infinite-dimensional systems, normalized coprime factorizations for well-posed linear systems, non-wellposed linear systems.

**G. Schneider:** weight distribution of convolutional codes.

**H.L. Trentelman:** control in a behavioral setting; pole placement and stabilization by interconnection, implementability of system behaviors, synthesis of dissipative systems; Hamiltonian and variational systems, algorithmic issues in systems and control; spectral factorization problems, algebraic Riccati equations; systems described by linear PDE’s.

**F. Tsang:** cyclic convolutional codes.

**G. Wanjala:** the study of the generalized Schur transformation, its effect on the (co-)isometric and unitary models and the corresponding basic interpolation problem for generalized Schur functions.

**R. Zavala Yoe:** Control as interconnection.
4.4 Publications

Contributions to books


Articles in scientific journals


**Articles in conference proceedings**


**Other publications**

4.5 External funding and collaboration

*External collaboration*

The Systems and Control group of the RuG collaborates with the Dutch Institute for Systems and Control (DISC). As the publication list illustrates, most members have collaborated intensively in scientific projects with colleagues from abroad.

For the operator theory project we have received an NWO grant for a three months visit of Prof. D. Alpay to Groningen. On April 1 a three years period came to end during which several exchange visits Nizhny Novgorod-Voronezh-Groningen were supported by NWO in the framework a cooperation between Russia and The Netherlands. We have applied for a continuation by another three years.

*International experience for graduate students*

Two of our permanent staff of four is Dutch and only one of our graduate students is Dutch. This means that English is the daily language. Moreover, our Ph.D. students follow the national graduate program in Systems and Control, which is organized by the Dutch Institute of Systems and Control, DISC. These are given in English. More than half of the students that participate in the graduate program of DISC are from outside the Netherlands. In addition, due to our research collaboration with colleagues from abroad, we have many guests from abroad each year. This creates an international environment in Groningen. Our Ph.D. students are funded to attend at least two international conferences during their Ph.D. period.

4.6 Further information

*R.F. Curtain* visited the Control groups at Imperial College and Worcester Polytechnic University for research collaboration and gave a seminar at MIT. She presented papers at three conferences: MTNS in Leuven, Belgium, Asian Control Conference in Melbourne, Australia, and at the CDC in The Bahamas. She is a member of the board for Exact Sciences of the Dutch Research Organization, (GBE,NWO).

*A. Dijksma* participated this year in four workshops: A Colloquium on Operator Theory (in honor of Prof. H. Langer on the occasion of his retirement, Vienna, March 4-6), the International Workshop on Operator Theory and its Applications IWOTA (Newcastle, July 12-15); a Conference on Differential Equations (in honor
of W.N. Everitt on the occasion of his 80-th birthday, Cardiff, July 19-21) and the fourth Krein space workshop (TU-Berlin, December 17-19). He was invited to give the Laudation for Heinz Langer at the colloquium.

*G. Wanjala* participated at the colloquium in Vienna and the workshop in Berlin, where he reported on his Ph.D research.

**H. Glüsing-Lürrsen:**

Since January 2003: Associate editor for SIAM Journal of Control and Optimization. She presented papers at 4 meetings: the AMS meeting in Athens (Ohio/USA), the IEEE International Symposium on Information Theory, Chicago (USA), the MTNS in Leuven (Belgium) and the Workshop on Algebraic Geometric Methods in Convolutional Codes in Salamanca (Spain). She was involved in the organization of the last two. She visited the Center of Ring Theory at Ohio University (USA) for research collaboration and she was a lecturer at the “IMA Summer Program for Graduate Students in Coding and Cryptography” held at the University of Notre Dame (Ind./USA).


**Orest Iftime** has been selected as an outstanding reviewer for Automatica for 2004.

**Mark Opmeer** presented papers at four conferences: Benelux in Helvoirt, MTNS in Leuven, Belgium, IWOTA in Newcastle, UK, and at the CDC on The Bahama’s.
5.  **Probability and Statistics**

**Group leader ad interim:** Prof.dr. W. Schaafsma

**Tenured staff (IWI members)**

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**Vacancies**

Professor in Probability and Statistics
Tenure track position

**PhD students**

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<td>Drs. C. Dechsiri (supervisor: Dehling and Hoffman)</td>
<td>RuG</td>
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<tr>
<td>Drs. S. Fleurke (supervisor: Dehling)</td>
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5.1 Research Program

The group fell apart in 2000 when Dehling became C4 professor in Bochum and Mikosch became professor and leader of a team in Copenhagen. They continued the supervision of PhD work started in Groningen. In the summer of 2000 it was decided that the chair in Probability and Statistics would be continued. The group continued its research in:

- applied probability theory and stochastic processes (Dehling and Mikosch)
- foundations of statistical inference (Schaafsma)

See Annual Report 2002 for a more extensive description. (The successor of prof.dr. W. Schaafsma and his U(h)D will have to reformulate the program such that it fits within the general policy of the faculty.)

5.2 Overview of scientific results

A lot of work was involved in revising the preprint of the book about distributional inference of Kardaun and Schaafsma. Many new issues appeared and these were tackled, often together with Dr. Albers and others. This work continues. The paper of Kardaun et al. published in 2003 was translated into Chinese; 2 parts appeared in 2004, further part(s) will follow. In this paper the views were expressed, somewhat implicitly, of what may be called The Groningen School of Statistics (See Rejoinder by Sir David Cox in the paper). A new manuscript was composed by Albers, Kardaun, Schaafsma, Steerneman and Stein about 'Foundational Issues in Statistical Inference' in which the views indicated are expressed more clearly. A paper by Albers, Kooi (Computer Science, now Philosophy) and Schaafsma about the 2-envelope problem was accepted by Synthese in 2003 but did not yet appear. It will hopefully appear in 2005. The Ph.D. work of De Bruin had its difficulties but it will, hopefully, be completed in 2005. A paper of Albers and Schaafsma about 'counting a frequency unseen’ was accepted by Statistica Neerlandica. It will appear in 2005. Albers, De Bruin, Schaafsma and the ornithologist De Roos are working hard on a booklet about a particular species of birds. It is a mixture of fundamental mathematical statistics, applied statistics, applied mathematics and, especially, ornithological practice.
5.3 Research Subjects

R. de Bruin: human growth and evolution, using definitions of size and shape
C. Dechsiri: stochastic modelling of transport phenomena in gas-solid fluidized beds, experimental aspects included
S. Fleurke: analysis of spectrum occupancy, applied probability
W. Schaafsma: foundations and applications of mathematical statistics

5.4 Publications

Dissertations


Articles in scientific journals


5.5 External funding and collaboration

External collaboration

O.J.W.F. Kardaun, Max Planck Institut für Plasma physik Garching, A. Stein, Wageningen University, C.J. Albers, Bioinformatics Groningen University, G.Th. De Roos, ornithologist, Vlieland.
6. Computational Mechanics and Numerical Mathematics

Group leader: Prof.dr. A.E.P. Veldman

Tenured staff (IWI members) source fte
Dr.ir. K.W.A. Lust (since 16-08-2004) RuG 1.0
Prof.dr. A.E.P. Veldman RuG 1.0
Dr.ir. R.W.C.P Verstappen RuG 1.0
Dr.ir. F.W. Wubs RuG 1.0

Tenured staff (other) RuG 0.5
Dr. E.F.F. Botta

Postdocs CMNM/BRCC 1.0
Dr.ir. G. Fekken (April 1 - December 31) 1.0
Dr.ir. G.E. Loots (since 01-07-2004) STW 1.0
Dr.ir. R. Luppes RuG/SRON 1.0

PhD students Min. O&W 1.0
Ir.drs. M.T. Dröge
(supervisor: Verstappen)

Ir. K.M.T. Helmholt–Kleefsman EU 1.0
(supervisors: Veldman, Wubs)

Ir. A.J.A. Kort NWO-CS 1.0
(supervisors: Wubs, Verstappen)

Ir. A.C. de Niet STW 1.0
(supervisor: Wubs)

Ir. G. Rozema (since 1-9-2004) RuG 1.0
(supervisor: Veldman)

Ir. R. Wemmenhove (since 15-03-2004) STW 1.0
(supervisor: Veldman)

Visitor STW 1.0
X. Trias, Universitat Polytècnica Catalunya, Barcelona, Spain
6.1 Research Program

With the continuing progress in numerical mathematics and computer technology, the impact of computer simulation on society is rapidly increasing. Our group is an active part of this dynamic scene, specializing in the numerical simulation of fluid dynamics and transport phenomena (Computational Fluid Dynamics CFD). On the one hand research is focussed on basic advancement of numerical algorithms; on the other hand - through extensive cooperation with external research groups - these methods are made available to advance knowledge in other (applied) areas of science and technology.

Turbulent flow: A main area of research concerns turbulent flow. Industrial simulation methods make use of turbulence models to keep computational effort within reasonable limits, but a price is paid in terms of accuracy. Thus research into higher-resolution methods, such as large-eddy simulation (LES) and direct numerical simulation (DNS) methods is essential. Our group concentrates on designing LES models and numerical techniques according to the preservation of analytical properties of the continuous flow equations.

Free-surface flow: Another main research area concerns the numerical simulation of free-surface flow in terrestrial and extra-terrestrial conditions. In cooperation with NLR an experiment is being prepared with a free flying spacecraft to study the influence of on-board liquid on spacecraft dynamics (flight scheduled for 11 February 2005). A fast-growing application area is maritime technology. In close cooperation with MARIN, our group is involved in long-year projects on wave loading on offshore platforms (funded by EU, STW and industry). Also (smaller) free-surface flow projects with academia and industry are supported. Basic tool is the in-house developed simulation method ComFlo.

Sparse-matrix solvers: The repeated solution of one or more systems of equations is part of any CFD method. Therefore the quest for improved matrix solvers is another major research area. A method (MRILU) is being developed which can cover a broad class of matrices: symmetric or non-symmetric, structured or unstructured. A major application area is the investigation of flow patterns in global ocean circulation (with UU-IMAU).

Bifurcation analysis: A new research area in the group is numerical bifurcation
analysis. Bifurcation analysis classifies the stability changes that can occur when one or more parameters in a mathematical model are changed. Our research focuses on numerical methods for large-scale problems, and more specifically, on numerical methods that operate on top of a simulation code. This may be a simulation code for a PDE system, but can as well be a lattice Boltzmann model or a “coarse-grained” simulator (using a multiscale simulation approach). In the near future we will also look at various fluid flow problems, such as flows over topography, climate models, Navier-Stokes flows and combustion problems. This will be done partly in collaboration with the Dynamical Systems & Analysis group.

*Engineering applications:* Various CFD applications are supported. In addition to the ones already mentioned, we report scientific projects in the areas of anatomy (arterial blood flow; with UU and AZG) and biomedical engineering (artificial organs). Again, ComFlo is the basic simulation tool. Further, extensive collaboration with the Dutch technological institutes is going on. Next to the projects with NLR and MARIN already mentioned, projects with WL|Delft Hydraulics and ECN-NRG are being defined. Finally, various cooperations with industry can be mentioned (see below).

### 6.2 Overview of scientific results

In 2004, the *DNS project* has focussed on three themes. Firstly, the symmetry-preserving discretization of boundary conditions at non-grid-aligned boundaries (cut-cell method) has been refined. A second-order implementation has been completed and is being validated with available benchmarks. Secondly, the discretization near (local) refinement boundaries has shown progress. Finally, attention has been paid to mathematics-based modelling for large-eddy simulation (LES).

The *free-surface projects* (ComFlo development) have made considerable progress in 2004. The MARIN-funded project on ship slamming has concentrated on the implementation of moving objects including the interaction between body motion and wave dynamics. A PhD thesis (Fekken) has been defended. Further, in the EU-funded Safe-FLOW project on wave loading in offshore applications the ComFLOW code has been delivered to the sponsors with a workshop in Singapore. The follow-up project ComFLOW-2 has been started. In this project the flow modelling will be extended towards two-phase flow, to include the effects of airentrapment during impact. As before, experimental validation support will be provided by MARIN, and benchmarking will be carried out by our Norwegian partner FORCE.
Figure 1: Simulation (ComFlo) versus experiment (courtesy Martin Greenhow, Brunel University) of a cylinder falling in water.

Technology. Finally, after a six-year delay, it is expected that the experimental Sloshsat spacecraft, designed by NLR, will fly early 2005. Herewith our ComFlo simulations of liquid behaviour under micro gravity will be validated.

The sparse-matrix project is closely cooperating with the Institute for Marine and Atmospheric Studies (IMAU) in Utrecht. The MRILU solver is being used to study stability and bifurcation patterns in ocean circulation. In 2004 the project on reconstructing the time-mean ocean circulation pattern has concentrated on refined preconditioners. Further, the MRILU solver has been implemented in one of the reservoir engineering codes at Shell (Rijswijk).

The hemodynamics project, on modelling and simulating elastic vessel walls and studying the secondary flow patterns in the embryonal heart, has received a follow-up in a newly started PhD project on modelling atherosclerosis in cooperation with AZG. Again ComFlo is our main simulation tool.

The numerical bifurcation analysis project was mostly based on a collaboration with the K.U. Leuven (Belgium), the previous employer of dr. Lust who joined the group in August 2004. Several experiments have been conducted on bifurcation analysis of lattice Boltzmann models, properties of the coarse-grained integrator for a lattice Boltzmann code and acceleration of time simulation of lattice Boltzmann models and coarse-grained simulations. Methods for the study of wave phenomena related to continuous symmetry in the mathematical models (travelling waves, spiral waves, etc.) and self-similar solutions have also progressed.
The major *industrial engineering projects* in 2004 involved cooperation with Bid-dle B.V. (indoor climate control), SasTech (sideways launching of ships), Wet&Dry (spray drying) and SCK-CEN (Belgium) (free-surface flow in a spallation target).

### 6.3 Research subjects

**E.F.F. Botta**: development of effective solution methods (algebraic multi-level ILU preconditioners) for sparse systems of equations in structured and unstructured problems.

**M.T. Dröge**: Cartesian grid methods for direct numerical simulation of turbulent flow.

**G. Fekken**: free-surface flow, spray drying.

**K.M.T. Helmholt–Kleefsman**: numerical simulation of hydrodynamic loading of offshore platforms.

**A.J.A. Kort**: local grid refinement for direct numerical simulation of turbulent flow.

**G.E. Loots**: hydrodynamic wave loading on floating and moored offshore structures.

**K.W.A. Lust**: numerical bifurcation analysis of large-scale systems, applications to fluid problems, lattice Boltzmann models and multiscale simulation techniques.

**A.C. de Niet**: reconstruction of the time-mean velocity field of the ocean circulation.

**G. Rozema**: fluid-structure interaction in viscous flows, with application in hemodynamics.

**A.E.P. Veldman**: development of simulation methods for various flow problems – turbulent flow, boundary-layer flow (domain decomposition), free-surface flow, industrial and biomedical flow problems.

**R.W.C.P. Verstappen**: development of simulation methods for turbulent flow (direct and large-eddy simulation DNS/LES).

**R. Wemmenhove**: hydrodynamic wave loading on floating and moored offshore structures.

**F.W. Wubs**: development of a multi-level ILU preconditioner for sparse systems; application to eigenvalue and continuation problems in the simulation of ocean circulation.
6.4 Publications

Dissertations


Articles in conference proceedings


6.5 External funding and collaboration

Our research policy focusses on strengthening the link between fundamental developments in mathematics and the scientific and technical needs from society; in-house developed software plays an essential role here.

External funding

Five out of our six IWI PhD projects are being funded externally from national and international resources. In 2004, the Dutch technology foundation STW awarded the ComFLOW-2 proposal (in cooperation with MARIN and TUD) on hydrodynamic wave loading on moored and floating offshore vessels (total budget 1.0 MEuro: 2 PhD positions, 1 post-doc position and experimental budget). Further, NWO-SRON awarded a one-year post-doc position for the SloshSat project (52 kEuro). Also, an NWO-NCF grant has been awarded to parallelize the ComFlo code (25 kEuro). Finally, some small contracts have been carried out for industry (Shell, Biddle BV, SasTech, Wet&Dry).
Societal relevance

As indicated above most of our PhD research is carried out in physical or technological applications (for details see above). Moreover, about 90% of our Masters’ projects are part of a cooperation with groups outside mathematics. In 2004 the latter projects involved (alphabetically) AZG, Biddle BV, MARIN, NLR, RuG Biomedical Engineering, SasTech and UU IMAU.

International collaboration

Various bilateral contacts exist with research groups outside the Netherlands, leading to e.g. traineeships for our Masters’ students and/or to joint publications. On a multilateral scale, a major project is the cooperation with MARIN and about two dozen off-shore companies throughout Europe, Northern America and Asia on hydrodynamic wave loading (Safe-FLOW project and its follow-up ComFLOW-2). Another project is the cooperation with NLR, ESTEC and NASA on the design and exploitation of the experiment satellite SloshSat FLEVO. Also cooperations with KU Leuven and University of Bristol (on numerical bifurcation analysis), University of Colorado (on global ocean circulation) and Oregon State University (on Langmuir circulation) deserve to be mentioned. Furthermore, the group takes part in the EU-funded networks ‘Eureka’ on artificial speech (coordinated by RuG Biomedical Engineering) and ‘Liquid management in space’ (coordinated by the University of Bremen).

6.6 Further information

Veldman is a member of the Scientific Committee NIVR-NLR, appointed by the Netherlands Agency for Aerospace Programs (NIVR), where he is involved in the Subcommittees on Aerodynamics and on Applied Mathematics and Information Technology. Also, he is a scientific consultant of the ICT division at the National Aerospace Laboratory NLR (Amsterdam). Further, Veldman is a member of the Advisory Board of the Maritime Research Institute MARIN (Wageningen). Finally, he is on the editorial board of Computers and Fluids and Journal of Engineering Mathematics.

In 2004, group members (co-)presented a total of 12 lectures (of which 11 invited) at national and international meetings, amongst which: 8th Conference on Iterative Methods (Copper Mountain), 14th Offshore and Polar Engineering Sym-
posium (Toulon), BAIL2004 on Boundary and Interior Layers (Toulouse), ECCO-MAS Computational Fluid Dynamics Conference (Jyvaskyla), OMAAE Symposium on FPSO Integrity (Houston), FPSO Weeks (Singapore and Paris), and 7th Drop Tower Days (Bremen). Also, an international workshop has been organized at the National University of Singapore.

The forthcoming launch of SloshSat has already attracted much media attention. A radio interview (Radio Noord) can be mentioned plus several items in (inter)national magazines and newspapers, e.g. Scientific American, Natuurwetenschap & Techniek, Volkskrant and some local newspapers.

An animated impression of the group’s research can be found at the website http://www.math.rug.nl/~veldman/cfd-gallery.html.
7. **Software Engineering**

**Group leader:** Prof.dr.ir. J. Bosch

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### 7.1 Research Program

The software engineering research group at the University of Groningen was established during the fall of 2000. At that point the group consisted of 3 persons, i.e. one professor, one assistant professor and one PhD student. Four years later the group has expanded substantially, currently consisting of one professor, two assistant professors, eight PhD students and six industrial PhD candidates. Within the field of software engineering, the main focus of the research group is on software architecture and software product families. The group employs an empirical research approach and extensive cooperates with the national and European software industry.

**Software Architecture**

Over the last decade, the software engineering community has come to the understanding that the challenging task of the development of software systems no longer is to provide the required functionality, but rather to fulfil the quality requirements of the system. Quality requirements, e.g. modifiability and usability, typically require explicit attention during development in order to achieve the required levels. Unfortunately, software engineers have few techniques available for predicting the quality attributes of a software system before the system itself is available and, consequently, to explicitly design for quality attributes.

Within the domain of software architecture, our research addresses two activities, i.e. assessment of quality attributes and the design of software architectures. The research towards assessment activities focusses particularly on assessment of usability and modifiability, but also other quality attributes, e.g. scalability, are considered. Quality attribute assessment starts with the precise, scenario-based specification of the quality requirement, i.e. a scenario profile. The architecture of the software system is consequently systematically assessed using the specified profile. The results of the assessment are quantified and exploited during the iterative design and evolution of the software architecture.

The research on software architecture design is concerned with the relation between quality attributes and design decisions and the difficulty of replacing or changing architecture design decisions once these have been taken. As an example of the first aspect: what is the effect of using a blackboard style for a software system on its performance and modifiability characteristics? In the context of the EU project STATUS, we investigate the relation between usability and software architecture. With respect to the second aspect, we have identified an increasing concern with the lack of flexibility of software architecture design decisions. Although this has long been accepted as a fact of life and has driven the attention towards ex-
plicit, up-front design of software architectures, during evolution also the software architecture typically has to evolve. In our research, we investigate approaches that allow for the first-class representation of architectural design decisions, during the architecture design phase, but also during later phases in the lifecycle. Finally, we study the notion of design erosion. As software evolves over time, it also ‘ages’, i.e. its suitability for its intended purpose decreases. In our research, among others in cooperation with Baan and Philips, we study the identification, repair and avoidance of design erosion.

The second main area of research within the group is software reuse, in particular in the context of software product families. A software product family consists of a product line architecture, a set of components and a set of products. Each product derives a software architecture from the product line architecture, instantiates and configures a subset of the product line components and contains some product specific code. The group studies, among others, the evolution and maturity of product families, scoping and organizational aspects, but our primary focus is on software variability management. Software variability refers to all locations in software artefacts where the behaviour of an artefact can be changed, adapted or extended. In our research, we develop a conceptual framework for variability management, approaches to visualize variability and representation, assessment and configuration approaches for variability management.

Dynamic software architectures are the third research area in the group. Dynamic software architectures can adapt themselves to changing environments and quality requirements at runtime. In our research we investigate the representation of runtime variability, quality, and architectures to accommodate for runtime dynamism.

7.2 Overview of scientific results

As discussed in the description of the research program, the main topics of the research group are in software architecture and software product families. In the overview of the scientific results, we present our contributions according to the following topics: software variability engineering, software architecture assessment and design, software product families and design erosion.

Software Variability Engineering
Promoting software reuse is probably the most promising approach to the cost-effective development and evolution of quality software. An example of reuse
is the successful adoption of software product families in industry. In a product family context, software architects anticipate product variation and design architectures that support product derivation in both space (multiple contexts) and time (changing contexts). Product derivation is based on the concept of variability: a single architecture and a set of components support a family of products. Modern software needs to support increasing amounts of variability. The reason for this is threefold. Firstly, variability is transferred from mechanics and hardware to software. For example, a dedicated feedback control unit implemented in hardware is replaced with a real-time software component that is selected from a set of components implementing different types of feedback controllers. Secondly, software introduces functionality that was not available before. For example, small-sized mobile phones are only possible with software, i.e., software provides new and more functionality ‘per cubic centimeter’ than other techniques such as dedicated hardware. Thirdly, there is a trend to delay design decisions to the latest moment in the lifecycle that is still economically feasible. For example, software systems adapt themselves to a changing environment using expert systems for selecting the appropriate components at run-time, i.e., variation points are bound just before certain functionality is required. The increasing amount of variability leads to a situation where variability engineering becomes of primary concern in software development. The number of variation points for industrial product families may range in the thousands, which is already a challenging number to manage, but the number of variability dependencies typically has an exponential relationship to the number of variation points, meaning that it is impossible to manage variability without systematic approaches. Implicit dependencies erode the architecture, making it harder to modify the system, but it also complicates the product derivation process, i.e., how to determine whether a particular product configuration is possible if the variability dependencies are not known?

We have introduced a Variability Categorization and Classification Model (VCCM) for representing variability in the software lifecycle. VCCM classifies a software system in one out of five maturity levels according to its predominant variation point binding times (e.g., during compilation or run-time). VCCM has been applied to the software product family of MRI scanners developed by Philips Medical System in a case study. Trying to answer the question “what types of variability dependencies exist in product family engineering?”, we have suggested a taxonomy of variability dependencies. The taxonomy is applied in two case studies. The first study is about designing a program monitor and exception handler for a legacy system, the second study outlines the development of a signal processing system that configures itself according to the input it receives, i.e., it is a self-adaptive sys-
The goal of the ConIPF project is to define and validate a methodology for product derivation in the context of software product families. The term product derivation refers to the process of constructing individual products from a collection of reusable software assets. During 2004, ConIPF continued its work on defining the methodology, and started with the validation aspects of the methodology during the experiment and assessment phase. Our work within the project focused on a framework for modeling the provided variability of a product family (COVAMOF), the associated tool support (Mocca), and a technique for assessing provided variability in the context of evolution (COSVAM).

COVAMOF (The ConIPF Variability Modeling Framework) is a variability modeling approach that represents variation points (locations in software artifacts at which a choice can be made) and dependencies on all abstraction layers (e.g. features, architecture, components) as first class citizens, supports the modeling of relations between dependencies, provides traceability and a hierarchical organization of variability throughout all abstraction layers, and supports intrinsic variability modeling.

COSVAM (The COVAMOF Software Variability Assessment Method) deals with the question of determining whether, when and how the provided variability of a product family should evolve. COSVAM is an assessment technique that consists of five steps, i.e. identify assessment goal, specify provided variability, specify required variability, evaluate variability, and interpret assessment results. It uses the COVAMOF to specify both provided and required variability.

Both COVAMOF and COSVAM have been applied at a Small-to-Medium Enterprise in the Netherlands, i.e. Dacolian B.V. The tool development for COVAMOF and the results of this case study have been published in three conference, and three workshop papers.

Software Architecture that supports Usability
Our research has been funded by the European Union funded STATUS (Software Architecture that supports Usability) project. STATUS was an ESPRIT project (IST-2001-32298) financed by the European Commission in its Information Society Technologies Program, Action Line IV.3. The project started on 1-12-2001 and
its duration was 36 months. The aim of this project was to gain an in-depth understanding of the relationship between software systems usability and architecture.

Our research in the STATUS project has been motivated by the understanding that usability is not something that can be easily "added" to a software product during late stage, since software quality is determined and restricted by architecture design. Assessing whether a software architecture supports the usability requirements is an improvement upon this situation and has been the focus of our research. As we take an "experience" based approach to software architecture assessment we captured existing design knowledge and turned architecture assessment into a repeatable process. The results of our research can be categorized in the following areas and has led to the following results:

- Capture existing design knowledge. ASUP: A collection of architecture sensitive usability patterns. SAU-framework: A framework which relates the collection of ASUP patterns to specific properties of usability. Bridging patterns: recently the concept of architecture sensitive usability pattern was refined to bridging pattern. Bridging patterns extend interaction design patterns by adding information on how to generally implement this pattern. Bridging patterns can be used for architectural analysis: when the generic implementation is known, software architects can assess what it means in their context and can decide whether they need to modify the software architecture to support these patterns.

- Turn architecture design into a repeatable process. SALUTA: Based on our investigations into the relationship between usability and software architecture, we developed a Scenario based Architecture Level Usability Analysis technique (SALUTA). SALUTA has been successfully applied at three industrial case studies performed in the domain of web based enterprise systems.

Architectural Design Decisions
Designing software is about making the right decisions at the right time. Making the right decisions improves the quality of the design and reduces future (maintenance) costs. Making the right design decisions in the right time shortens development time of the system and increases the value of the design for the involved stakeholders. Especially, for software architectures this is the case. As a software architecture is the fundamental design of a software system, architectural design decisions have a major impact on the resulting quality, costs, and timeliness of the system. Consequently, research in software architectures has focused on mak-
ing a software architecture complete and correct from the start, as experience has learned that changing a design later on is very difficult and expensive. However, although design decisions play such an important role in making a design complete and correct, they are not explicitly visible in these designs. Software architecture documentation and modeling approaches only show the result of a design decision implicitly embedded in the resulting description of the architecture. Consequently, the architectural design decisions underlying the architecture become lost. This lost information is leading to problems of design erosion and complexity, which result in high costs for change and maintenance. One line of research is an analytical one. First a survey is written about the current state of the art in documenting design decisions. Secondary, an analyses of the ways in which rationale about the decisions can be written down is being made, in the form of a book chapter. The next step is the observation of the decision process in practice, and analyses of how new systems can be used to decrease the amount of lost information. Another line of research focusses on first class modeling of architectural design decisions and its associated problems. On the basis of this work, a survey was made on existing tool support for software architecture and the way they dealt with design decisions. The next step in our research focussed on how architectural design decisions can be first class modeled in software architectures. To this end, a conceptual model was created about the relationship between design decisions and a software architecture. This conceptual model views a software architecture as a set of design decisions, which make the architecture. To validate this conceptual model, a more concrete model was made, which forms the basis of the Archium approach. Archium (www.archium.net) is a component language extending the Java programming language. It supports architectural concepts like component, connectors, and also design decisions first-class. Software architectures in Archium are a set of design decisions. A compiler and run-time platform support the Archium language, which allows for run-time addition of additional design decisions.

7.3 Research subjects

L. Bakalis: software architecture and usability
J. Bosch: software variability management, software architecture assessment and design, software product families, design erosion.
J. Bosloper: dynamic software architecture, software variability, tool support
S. Deelstra: software product families and software variability evolution
F. Erazo: usability in relation to software architecture
E. Folmer: software architecture and usability.
A. Jansen: architectural design decisions
M. Jaring: variability engineering in software product families.
T.D. Meijler: concepts for realizing for software variability management
J. Nijhuis: dynamic software architecture
J. Siljee: dynamic software architecture, service-centric systems
M. Sinnema: software product families and variability representation
R. Smedinga: software families architecture design decision representation
J. van der Ven: architectural design decisions

7.4 Publications

Dissertations


– R. van Ommering, Building Product Populations with Software Components, Promotor: J. Bosch, Faculty of Mathematics and Natural Sciences, University of Groningen, 03-12-2004, 218 pages.

Edited books


Book chapters

Articles in scientific journals


Articles in conference proceedings


Other publications

Workshop papers


7.5 External funding and collaboration

External funding The research of E. Folmer, F. Erazo, J. van Gurp and L. Bakalis is financed through the ongoing EC-IST STATUS project. The research of S. Deelstra, M. Sinnema, J. Siljee and I. Bosloper is funded through the ongoing EC-IST CONIPF project.

External collaboration

Six industrial Ph.D. students are connected with the group:
R. van Ommering (Philips Research): Product populations and the Koala component model.
A. Maccari (Nokia Research): Architecture centric software development and evolution.
S. Stuurman (Open Universiteit): Software architecture representation and design decisions.
E. Kesseler (National Aerospace Laboratory NLR): Reliability and Software Architecture.

7.6 Further information

Workshop organization

Ninth Workshop on Component-Oriented Programming Workshop associated with

Bosch was member of, among others, the following programme committees:

**Program committees**


Program committee co-chair, Eight International Conference on Software Reuse (ICSR 8), Madrid, July 2004.


Third International Conference on Generative Programming and Component Engineering (GPCE 2004).

In addition, Bosch is member of the following steering committees: Working IFIP/IEEE Conferences on Software Architecture, since 2001, Generative and Component-based Software Engineering Conferences, since 2001.

Also, Bosch (co-)organized a workshop on Software Variability Management at the University of Groningen (February 2003), the Software Variability Management workshop in association with the 25th International Conference on Software Engineering (ICSE 2003) in May 2003, together with Peter Knauber (Mannheim University of Applied Sciences), the workshop on Bridging the Gaps Between Software Engineering and Human-Computer Interaction, also in association with
the 25th International Conference on Software Engineering (ICSE 2003) and the Eighth Workshop on Component-Oriented Programming associated with the 16th European Conference on Object-Oriented Programming (July 2003) with Clemens Szyperski (Microsoft Research) and Wolfgang Weck (Oberon Systems).

He gave, among others, the following tutorials and invited talks: Software Architecture Assessment, seminar at National Aerospace Laboratory NLR, Amsterdam, February 2003; Designing Software Architectures for Usability, Tutorial at ICSE 2003 together with Natalia Juristo (UPM, Spain), May 2004; Variability in Software Product Families, seminar at the University of Calgary, Canada, May 2003; Software Product Families in Large Companies, seminar at Software Variability Summer School, Edmonton, June 2003; Architecture-centric Software Engineering, tutorial at ECOOP 2003, July 2003; Software Variability Management, tutorial at ECOOP 2003, July 2003; Bouwen aan Innovatie, Invited talk SPIDER Conference, Eindhoven, September 2003; Software Product Families: Maturity and Variability, iCORE presentation at University of Calgary, Canada, November 2003; Maturity and Variability in Software Product Families, INTUIT, Edmonton, Canada, November 2003; Software Architectuur in de Lage Landen, invited presentation at Landelijk Architectuur Congres, Golden Tulip Figi, Zeist, November 2003;

During 2003 Nijhuis was article reviewer for numerous journals. He is member of the editorial board of PR Embedded Systems (ten Hagen & Stam). He gave invited talks on dynamic software architectures at IBM Netherlands and TNO FEL.

In 2004 Smedinga was secretary in the board of NIOC and co-organizer of NIOC2004, a conference on the education of computing science in the Netherlands, organized in Groningen at 3 and 4 November.
8. Fundamental Computing Science

**Group leader:** Prof.dr. G.R. Renardel de Lavalette

**Tenured staff (IWI members)**

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8.1 Research Program

The objective of this programme is to contribute to the understanding of the logical and mathematical foundations of computing science and to realize a two-way transfer between this fundamental research and more applied subdisciplines of computing science. Our research focuses on formal methods, which are based on concepts and theories from discrete mathematics and logic. They are applied to enhance the reliability of computer systems and computer software, and also to further the understanding of the possibilities of computing in general. The following themes are studied: equational reasoning, modal and dynamic logic, multi-agent systems, security, programming methodology, decision support systems.

Equational reasoning is a well-known kind of mathematical reasoning that is practised e.g. in algebra and in many correctness proofs. Its standard formalization is equational logic, a simple but very general reasoning system that is often used in computing science, e.g. in algebraic specification and rewrite systems (Mathematica is a well-known example). Proof theory for this logic, addressing structural properties of equational proofs, hardly exists, and the group tries to fill in the gap.

Modal logic studies reasoning involving modalities like it is necessary that . . . , I know that . . . , you believe that . . . , etc. They are applied frequently in Artificial Intelligence research. We concentrate on dynamic logics, addressing reasoning about change, and on hybrid logic, an interesting recent extension of modal logic. We focus on fundamental properties like completeness: is a given proof system strong enough to prove all true statements?

Multi-agent systems (MAS, also known as Agent Computing or just Agency) is a subdiscipline of both Computing Science and Artificial Intelligence. Agents are intelligent, possibly mobile processes to which intentions can be attributed: beliefs, desires and commitments. A multi-agent system consists of agents that cooperate to perform a task. As an example, think of a travel agency trying to compose a holiday trip that best fits the client’s wishes: this requires collaboration between the agents that perform subtasks such as hotel booking and airplane reservation. MAS is inspired by process theory and concurrency on the one hand, and logic and formal specification on the other hand. Process theory and concurrency provide the notion of concurrent and communicating processes; logic (especially modal logic) and formal specification provide high-level languages for description of and reasoning about agents and their intentions. We try to apply the logical approach in concurrent algorithm design for MAS.

Security is a very active research area. We started investigation of quality aspects
of security protocols: under what conditions do they guarantee that secrets become known to some party while remaining secret for other parties? This is another application area for epistemic dynamic logic.

For programming methodology, the group aims to contribute to the design, specification, and verification of sequential, parallel and distributed algorithms, programs, and systems. We prove properties of such algorithms or systems by assertional means, i.e., by reasoning about individual states and computation steps, rather than considering entire execution sequences. Even so, seemingly modest algorithms may require a host of case distinctions that a human prover finds difficult to control. In such situations, we use mechanical theorem provers for the administration of proof obligations.

The research in decision support systems focuses on medical realtime support systems (e.g. monitoring and warning systems for anesthesia and intensive care). For a smooth interaction with the user, such systems must have some kind of user awareness, i.e. they must know about the cognitive activities and the mental state of the user. This research subject combines two disciplines: human-computer interaction and artificial intelligence.

8.2 Overview scientific results

Burza worked with Hesselink and Renardel on the analysis of security protocols using epistemic logic and action structures.

Gao and Hesselink designed with Groote (TUE) a distributed garbage collection algorithm based on the synchronization primitives load-linked/store-conditional. Gao developed a reduction theorem for lock-free patterns in concurrent programs based on compare-and-swap registers.

De Haan, Hesselink and Renardel worked on the modelling and programming of multi-agent systems. They use the game Mafia as an example, a social interaction game where knowledge, beliefs and suspicions play an important role.

Hesselink worked with Roerdink (IWI, research programme 10) on computational skeleton definitions for binary images.

Le Feber and Pott finalized with Fetchenhauer (Köln) a paper on the results of an international survey on the improvement of real time medical support systems. With Ballast (Academic Hospital Groningen) they developed a model that estimates the cognitive workload of anesthesiologists during operations.
Renardel continued the development of structural proof theory based on abstract derivations, leading to a constructive proof of interpolation for equational logic. With Kooi and Verbrugge (RUG, Artificial Intelligence), he investigated strong completeness of infinitary modal logics, establishing interesting results for hybrid logics.

8.3 Research subjects

Burza: application of dynamic logic to security.
De Haan: concurrency, agent computing, knowledge-based programming.
Gao: application of mechanical theorem provers to the verification of concurrent algorithms.
Hesselink: design and verification of concurrent algorithms.
Le Feber: development of a knowledge and classification system for diagnoses.
Pott: analysis of the survey results, design of a anesthesia monitor based on the survey results.
Renardel: proof theory of equational logic; modal and dynamic logic.

8.4 Publications

Articles in scientific journals


**Articles in conference proceedings**


**Other publications**


8.5 External funding, collaboration and internationalization

Hesselink and Gao collaborate with Groote (Eindhoven University).
Le Feber and Pott work in the project Requirements Engineering for Medical Realtime Advice Systems, led by Renardel de Lavalette and funded by NWO. There is close collaboration with Ballast (Academic Hospital Groningen) and other anesthesiologists.
Renardel collaborates with Kooi (Philosophy, Groningen) and Verbrugge (Artificial Intelligence, Groningen) on several subjects in modal and hybrid logic.

8.6 Further information

Hesselink is member of the Board of the Dutch Research School IPA (Institute for Programming Research and Algorithmics).

Kooi, who defended in 2003 his Ph.D. thesis Knowledge, Chance and Change written under the supervision of Renardel, received in 2004 the Van Swinderen Prize for the best Dutch summary of a Ph.D. thesis defended in 2003 at the Science Faculty or Medical Faculty at Groningen University.

Renardel is member of the Board of the Dutch Research School in Logic, and member of the Board of the Dutch Society for Theoretical Computer Science.
9. **Intelligent Systems**

**Group leader:** Prof.dr.sc.techn. N. Petkov

**Tenured staff (IWI members)**

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<td>Dr. M.H.F. Wilkinson</td>
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**Guests**

- Prof. Dr. J.K. Anlauf, University of Bonn, Germany
- Dr. G. Bhanot, IBM Research Yorktown Hights, USA
- Mrs. C. Calidona, CNR Instituto di Cibernetica Naples, Italy
- Dr. P. Campisi, University of Rome Tre, Italy
- Dr. L. Florack, Technical University of Eindhoven, Netherlands
- Prof. Dr. B. Hammer, University of Osnabrück, Germany
- Prof. Dr. W. Kinzel, University of Würzburg, Germany
Guests (cont.)
Dr. D. Malzahn, University of Karlsruhe, Germany
Prof. Dr. S. Mitra, University of California at Santa Barbara, USA
Prof. Dr. H. Neumann, University of Ulm, Germany
Prof. Dr. M. Nielsen, Copenhagen IT University, Denmark
Ms. L. Sanchez Gonzalez, University of Leon, Spain
9.1 Research Program

The research program Intelligent Systems includes interrelated topics from image processing, computer vision, pattern recognition, machine learning and neural networks.

*Biologically motivated computer vision*

Models of the visual cortex are developed and used in computer algorithms. This research is relevant for the areas of image processing, computer vision, pattern recognition, visual perception, and computational neuroscience. Our goal is to understand how humans see and to deploy principles of natural vision in artificial vision systems. Using facts from neuroscience and visual perception, we build models of visual neurons and use them in computer simulations to obtain insights and derive practical computer vision algorithms.

One example is the model of a grating cell that we developed [Petkov and Kruizinga: 1997 *Biological Cybernetics* 76 (2) 83-96] and used in a texture operator [Kruizinga and Petkov: 1999 *IEEE Transactions on Image Processing* 8 (10) 1395-1407], [Grigorescu, Petkov and Kruizinga: 2002 *IEEE Trans. on Image Processing* 11 (10) 1160-1167]. By means of computer simulations we demonstrated that grating cells may play an important role in the disambiguation of edge information in early vision (texture vs. contours). In contrast to traditional texture operators used in image processing, the texture operator derived from a computational model of a grating cell responds only to texture and does not respond to non-textural features, such as object contours.

Another example is our model of non-classical receptive filed inhibition, also called surround suppression, in groups of orientation selective neurons [Petkov and Westenberg: 2003 *Biological Cybernetics* 88 236-246]. This biological mechanism was simulated and applied to a large number of natural images. We demonstrated that the biological role of this inhibitory mechanism is quick pre-attentive detection of object contours and region boundaries in natural images that are rich in texture. We proposed various contour detection algorithms that deploy this mechanism and showed that they are more effective in detecting object contours and region boundaries than traditional computer vision algorithms for edge detection [Grigorescu, Petkov, Westenberg: 2003 *IEEE Trans. on Image Processing* 12 (7) 729-739], [Grigorescu, Petkov, Westenberg: 2004 *Image and Vision Computing* 22 609–622].
Currently we extend our research on the use of Gabor filters to the area of motion analysis. Another new research direction is the development of a method for the evaluation of the robustness of shape recognition algorithms to incompleteness of contours. This direction is inspired by similar psychological research on humans. Recently we started developing algorithms that mimic perceptual grouping by humans. One envisaged application is texture analysis.

**Image processing and computer vision**

In texture analysis we develop structural methods aimed at identifying a texel, i.e. a minimum size texture patch that is characteristic of a given texture.

In shape analysis we study geometrical approaches in which a feature point is characterized by the spatial arrangement of other feature points around it. The collection of local geometrical descriptors for the different feature points of an object is used as a shape characteristics of that object. We study the potential of this approach for object segmentation and classification in natural scenes in practical applications such as traffic sign recognition and image database retrieval [Grigorescu and Petkov: 2003 *IEEE Trans. on Image Processing* **12** (10) 1274-1286]. With inspiration from psychological research, we also study the robustness of shape recognition algorithms to incomplete contour representations.

Connected filters are a comparatively new field of research within mathematical morphology. They are edge preserving operators which have found use in noise removal, texture analysis, image compression and description, and feature extraction. Research on connected operators in our group entails algorithm development (including parallelization), development of new classes of filters, applications to 2-D and 3-D medical images, and the development of new connectivity measures for these filters for increased robustness. One line of this research links to visual cortex modelling: developing morphological analogues of texture operators based on models of certain visual cortical cells. It is hoped these morphological counterparts will be an order of magnitude faster, whilst retaining the useful properties of the cortical cell models. Finally, fast visualization based on connected attribute filters is being explored.

Segmentation is a core problem in image analysis, and methods based on both simple thresholding methods and more advanced methods such as watersheds and deformable models are being explored. Application areas are many, but the focus lies on biomedical imaging, both macroscopic (MRI, CT) and microscopic.
Machine learning and neural networks

Systems of adaptive information processing, such as neural networks, can be applied in variety of classification or regression problems. Their ability to learn from example data makes it possible to implement tasks which are not easily formulated as a simple set of rules, but for which example data are available.

We aim at a theoretical understanding of such learning processes based on the investigation of model systems. Besides analytical tools, computer simulations are employed in this context. The obtained insights allow to understand and predict phenomena which are also relevant in real world learning problems. Furthermore, they enable us to systematically develop and improve practical training algorithms.

As just one example, we are currently investigating methods of classification which are based on representing the data by prototypes. The so-called Learning Vector Quantization is a widely used approach, but lacks through theoretical understanding and systematic investigations of the typical algorithm performances.

We are furthermore studying networks of so-called Integrate-and-Fire units which model the behavior of biological spiking neurons. We aim at understanding of, for instance, masking effects in the first few layers of the visual system.

9.2 Overview of scientific results

Biologically motivated computer vision

In the article "Contour and boundary detection improved by surround suppression of texture edges" [Grigorescu, Petkov, and Westenberg: 2004 Image and Vision Computing, 22 609–622] we deployed a biologically motivated surround suppression mechanism to improve the detection of object contours and region boundaries in natural scenes. The essence of this mechanism is that the response of an edge detector in a certain point is suppressed by the responses of the operator in the region outside the area of operator support (Fig.2).

We illustrate the principle and the effect of surround suppression by adding this step to the Canny edge detector. The resulting operator responds strongly to isolated lines and edges, region boundaries, and object contours, but exhibits a weaker or no response to texture edges. Additionally, we introduce a new post-processing method that further suppresses texture edges. We use natural images with asso-
Figure 2: A natural input image and its desired output contour map (first row). Best binary contour maps obtained for the Canny edge detector (second row), SUSAN edge detector (third row), anisotropic and isotropic surround suppression augmented operators (fourth and fifth row, respectively). (From C. Grigorescu, N. Petkov, and M. A. Westenberg, Contour and boundary detection improved by surround suppression of texture edges, *Image and Vision Computing*, 22 2004, 609–622.)
associated subjectively defined desired output contour and boundary maps to evaluate the performance of the proposed additional steps. In a contour detection task, the Canny operator augmented with the proposed suppression and post-processing step achieves better results than the traditional Canny edge detector and the SUSAN edge detector. The performance gain is highest at scales for which these latter operators strongly react to texture in the input image.

*Image processing and computer vision*

In the article "Recognition of objects with incomplete representations" [N. Petkov and A. Ghosh: *Int. Conf. Adv. Concepts Intell. Vis. Systems 2004*, Brussels, Belgium, Aug. 31-Sept. 3, 2004, pp. 91-95] with inspiration from psychophysical researches of the human visual system we propose a method for the evaluation of the robustness of shape recognition algorithms to incompleteness of contours. We use the complete contour representations of objects as a training set and incomplete contour representations of the same objects as test sets (Fig.3(a)). The algorithms compared in this framework use shape context and distance multiset as local shape descriptors. Their performance is found to be very good if at least 30% and 3%, respectively, of the contour pixels are retained (Fig.3(b)). Both algorithms mimic human visual perception in the sense that recognition performance monotonously increases with the degree of completeness.

In image segmentation the following results were obtained. A method based on watersheds using automatic selection of markers was developed for segmentation of diatom images has been accepted for publication in Machine Vision and Applications. A new deformable shape model based on charged particles, which overcomes many of the shortcomings of snakes published in IEEE Trans. Pattern Anal. Mach. Intell.). In particular, the Charged Particle Model (CPM)does not require precise initialization, unlike snakes. Though similar results can be obtained through PDE-based methods, these are considerably slower. A study focusing on initialization was published in the proceedings of International Conference Image Analysis and Recognition (ICIAR) 2004

A comparison of multivariate pattern spectra with classical pattern spectra for texture analysis was completed, showing our multivariate method performs better when rotation invariance is needed. The initial results have been published in the proceedings of *Int. Conf. Pattern Recognition (ICPR) 2004*. A more extensive study, which showed image classification of images and textures in the Brodatz, COIL-20 and COIL-100 databases with a performance of up to 98.9 correct clas-
Figure 3: (a) Row 1: Sample of the complete contour images used as a training set. Rows 2 and 3: Incomplete contour images obtained by retaining 50% and 20%, respectively, of the contour pixels. (b) Recognition rate as a function of the percentage of contour points retained.
Figure 4: Removal of letters using shape priors and vector-attribute filters in a gray-scale image (a). By using an image of the letters A, B, and C as a shape prior, and using moment invariants of these shapes as attribute vector, shapes similar to the letters A, B, and C are removed from images (b), (c), and (d) respectively.

The theory of connected filtering was extended in various ways. First, a generalization of the existing second-order connected filters has been proposed, along with an efficient algorithm for their computation. These findings have been accepted for publication in the proceedings of the International Symposium for Mathematical Morphology (ISMM) 2005.

Second, attribute filters based on vector attributes rather than scalars have been proposed. Apart from allowing filtering based on a wider range of properties, the theory also allows definition of granulometries based on vector attributes, which could be used in texture analysis and content-based image retrieval. These filters also allow filtering based on shape priors, in which the filter is tuned by one or more example shapes, plus a tolerance, rather than by arbitrary thresholds. An example is shown in Figure 4. These results have also been accepted for the proceedings of the ISMM 2005.

A problematic property of so-called partitioning-based second-order connectivity was proven, and a possible solution proposed. In a partitioning-based connectivity, object linked by narrow “bridges” are split apart, and the pixels in the bridges are treated as singletons. This destroys all spatial information contained in the bridge regions. If the bridges themselves are of interest, as in the case of dendrites in neural images, this is unacceptable. As a solution, a new class of filter called attribute-space connected filters was proposed, in which the image is first embedded in a higher dimensional space (the attribute space), in which the connected filtering takes place. The resulting filtered volume is then projected back into im-
Figure 5: Elongation filtering of neurons: (a) binary image of neuron; (b) opening by ball of radius 3 to separate cell body from dendrites; (c) second-order connected attribute thinning preserving elongated features, which fails to find elongated features in (a) due to partitioning of dendrites into single pixels; (d) attribute-space connected filter result using same elongation criterion. Dendrites are detected in the latter case.

age space. An example can be seen in Fig. 5. The initial results were also accepted for the proceedings of the ISMM 2005.

Combining visualization with connected filtering was improved this further year. An earlier implementation of isosurface browsing and rendering directly from a filtered Max-tree was improved. In isosurface browsing we achieve frame-rates of up to 35 frames per second. The method is shown to be slightly faster than interval trees in isosurface browsing, and far superior in performance when browsing the filter parameters. These results and the earlier ones on direct volume rendering by splatting have been submitted to IEEE Trans. Visualization Comp. Graph. The methods allow interactive filtering of volume data sets, with immediate visualization of the results.
Morphological hat-transform scale spaces based in multiple dimensions were developed. The 1-D case was used for curvature analysis (accepted by IEEE Trans. Image Proc.); the 2-D case used for texture analysis has appeared in Pattern Recognition. These hat-transform scale spaces form a multi-scale representation of images or signals, based on analysis of the critical scales at which the topology of the image changes. They are useful for shape recognition, image segmentation and content-based image retrieval.

**Machine learning and neural networks**

Learning Vector Quantization (LVQ) is an intuitive, mostly heuristic approach to the supervised analysis of clustered data. It is, furthermore, closely related to the concept of self-organizing maps (SOM) or similar methods. Various modifications of LVQ have been suggested, aiming at faster convergence, better stability etc. A systematic theoretical study of these schemes, however, is lacking to date.

As a first step, we have analyzed a simple model scenario of LVQ in high dimensions exactly. Under certain simplifying assumptions, the typical dynamics of incremental LVQ is described exactly by means of coupled ordinary differential equations. Our approach allows to study systematically the influence of algorithm parameters, initial conditions etc. on the training process.

Our first results explain, for instance, why several suggested training schemes fail due an inherent instability when one of the classes is infrequently found in the data set. In the frame of our model situation we can show that Kohonen’s original formulation of LVQ typically yields a suboptimal learning curve, corresponding to a non-monotonic behavior with the number of example data. However, the procedure yields a close to optimal performance when a large number of examples is available.

A generic problem of training processes is relevant when the dimension of the data, and hence the number of adjustable parameters in the network, is large. Practical experience and theoretical studies show that the success of learning can be significantly delayed due to the existence of quasi-stationary states in the training process. These so-called plateaus occur in a variety of learning scenarios and are by no means restricted to the supervised training of multilayered networks.

One aim of our research efforts is to overcome, as far as possible, this plateau problem. We have suggested a prescription which, in a first step, reduces the dimensionality of the learning problem drastically by means of a modified Principal
Component Analysis technique. Ongoing research concerns the optimization of the algorithm with respect to regression and classification tasks. We furthermore aim at using the prescription as a tool for model selection, as it provides information about the complexity of the problem before the actual training is performed.

9.3 Research subjects

M. Biehl: machine learning, artificial neural networks, biologically inspired models
A. Ghosh: robustness of shape recognition methods to incomplete representations
D.J. Kamerman: computer simulation of the intestinal microflora
G.K. Ouzounis: generalized connectivities for morphological filtering
G. Pappari: texture, perceptual grouping
N. Petkov: texture, shape recognition, contour detection, psychophysics
K. de Raedt: visual memory, categorization
E.N. Subramanian: motion
E.R. Urbach: morphological analogues of biologically inspired texture operators
M.H.F. Wilkinson: morphological image analysis, biomedical modelling

9.4 Publications

Dissertations


Articles in scientific journals


Articles in conference proceedings


Other publications


9.5 External funding and collaboration

External funding

The position of Pappari is financed by a grant to Petkov in the open competition 2002 of NWO Exact Sciences. The position of Ouzounis is financed by a grant to Wilkinson in the open competition 2001 of NWO Exact Sciences.

External collaboration

Biehl collaborates with R. Urbanczik (Univ. Bern, Switzerland) in the development and investigation of efficient training algorithms for multilayered artificial neural networks. A theoretical understanding of the training of networks in the context of neural cryptography is the objective of an on-going collaboration with Kinzel (Univ. Würzburg, Germany). A common project B. Hammer from the Technical Univ. Clausthal-Zellerfeld, Germany, concerns the study and application of Learning Vector Quantization. Earlier contacts with BMW (Munich, Germany) have been re-established: the aim is to investigate application relevant neural architectures together with J. Anlauf (Univ. Bonn, Germany). A collaboration with N. Caticha from the Univ. of Sao Paulo, Brazil, and with P. Riegler (Fachhochschule Braunschweig, Germany) concerns networks of Integrate-And-Fire neurons and masking effects in the visual system. In the area of computational science Biehl
collaborates with the groups of W. Kinzel in Würzburg and M. Kotrla and Academy of Sciences in Prague. He gave invited talks at a Mini-Workshop on Multiscale Modeling at the Mathematisches Forschungsinstitut Oberwolfach and was invited for colloquia at the Universities of Bonn, Würzburg, and Utrecht.

Petkov gave a talk at a meeting on Measuring and Modelling Perception of the European Graduierten Kolleg Groningen-Oldenburg in January. In February he visited the Institute for Physiology of Bulgarian Academy of Sciences, Sofia (A. Vasilev) and gave a presentation of an internet enabled image processing operator. In March he visited Th.A. Lippert and gave a talk at the Central Institute for Applied Mathematics (ZAM) in Jülich, Germany. In April he visited University College London (Zh. Li), Adastral Campus of UCL (F. Stentiford) and British Telecom in Ipswich, Imperial College London (D. Rueckert) and University of Northumbria, Newcastle (M. Angelova, J. Edwards, J. Railey) and gave talks. In May he visited the University of Rome Tre (P. Campisi, M. Carli, A. Neri), gave a talk and signed a formal cooperation agreement within the Socrates programme of the EU. Also in May he gave a talk at the Institute of Advanced Computer Studies, University of Leiden (H. Wijshof, M. Lew). In June he visited the University of Naples (L Cordella, P. Foggia) and gave a talk. Also in June he visited the University of Salerno (M. Vento), gave a talk and signed a formal cooperation agreement within the Socrates programme of the EU. In July he participated in the Summer School on Cognitive Science in Sofia. In August he participated in the European Conference on Visual Perception in Budapest where he presented four posters. In September he gave an invited talk at the conference on PDE in Applied Mathematics and Image Processing in Slanchev Bryag, Bulgaria. In November he participated in the examination committee for PhD the defence of Oriol Pujol Vila at Universita Autonoma de Barcelona and visited the national Center for Computer Vision in Barcelona (P. Radeva) where he gave a talk. Also in November he visited the Institute for Cognitive Systems of the University of Kiel (G. Sommer) and gave a talk. Also in November he gave a talk at a workshop on neuroinformatics organized by NWO and ZON in The Hagues. Petkov was visited by the following scientists who gave talks at the Institute: M. Nielsen (Copenhagen IT University, Denmark; March), P. Campisi (University of Rome Tre, Italy; April), M. Pietikainen (University of Oulu, Finland; June), L. Florack (Technical University of Eindhoven, Netherlands; September), S. Mitra (University of California at Santa Barbara, USA; September), C. Calidona (CNR Instituto di Cibernetica Naples, Italy; September), H. Neumann (University of Ulm, Germany; November), G. Bhiont (IBM Research Yorktown Hights, USA; December), L. Sanchez Gonzalez (University of Leon, Spain; October-December).

Wilkinson conducts a project on simulation of the human intestine in collabora-
tion with the International Study Group on New Antimicrobial Strategies (ISGNAS: http://www.isgnas.org/). He collaborates with the Radiology and Dermatology departments of the Academic Hospital in Groningen in an NWO-project. A further collaboration with the Department of Biomedical Engineering, University of Groningen, concerning image analysis of scoliosis is also underway. Within this project a collaboration with B. Brendel and S. Winter of the Ruhr-Universität Bochum has also been initialized. He will also contribute to the collaboration on genomics analysis. He was invited to speak at the National Research Institute for Mathematics and Computer Science (CWI) Signals and Images Seminar in Amsterdam where he spoke on “Attribute Filters in Image Processing and Visualisation – or: One-Hundred-and-One Uses of a Max-Tree.” He was also invited to speak at the Euro-GK seminar in Groningen where he gave a lecture entitled “Connectivity-Preserving Filters in Morphological Image Analysis.” He was invited by the students at the IWI to give a similar talk at the undergraduate colloquia organized by the FMF. He was session chair at the 10th Annual Conference of the Advanced School for Computing and Imaging (ASCI) in Port Zélande, June 2-4 2004, and was invited to be teacher at the Mathematical Morphology course of ASCI.

9.6 Further information

Petkov is member of the editorial boards of Journal of Neural, Parallel and Scientific Computations (Dynamic Publ.), Parallel Algorithms and Applications (Gordon and Breach) and Real-Time Imaging (Academic Press). He is member of the scientific-technical council of foundation SURF and the International Advisory Board of the Knowledge Engineering and Discovery Research Institute, Auckland University of Technology. He is chairman of the steering committee of the CAIP (Int. Conf. on Analysis of Images and Patterns) series of conferences; the next 11th conference is in Paris, September 2005. He was member of the programme committee of the International Conference on Pattern Recognition (Cambridge, 2004).

Wilkinson was member of the programme preparation committee of the GLANCE programme of the Netherlands Organisation for Scientific Research (NWO). He is member of the steering committee of the Old Herborn University Seminars.
10. **Scientific Visualization and Computer Graphics**

**Group leader:** Prof. dr. J.B.T.M. Roerdink

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10.1 Research Program

The research group Scientific Visualization and Computer Graphics carries out research in the area of scientific visualization, computational geometry and geometric object modelling. The group has a strong orientation towards precise and verifiably correct algorithms. With respect to applications, the research concentrates on fundamental and applied problems from the life sciences. This concerns in particular functional brain imaging and bioinformatics.

Visualization of large data sets requires advanced techniques in image processing, hierarchical data management, and data reduction. This covers a wide range, from classical medical imaging to simulation of natural phenomena. Data volumes generated by scientific simulations can easily grow into the range of giga-bytes. Medical scanners routinely generate data volumes with a resolution of $512^3$ voxels, whereas scanners like multi-slice CT generate more than 1000 image slices in one scan. In a functional neuroimaging experiment (PET, fMRI), a large number of data volumes is obtained, thus increasing data size even further. Both the increasing size and complexity of these data ask for new techniques for interactive visualization. The possibility of interaction during evaluation will significantly reduce the time required to interpret and present results.

To arrive at interactivity for large data sets, a number of techniques are available, such as auxiliary data structures; special (multiresolution) data transforms, e.g., wavelets or multiscale morphological methods; extraction of features from the volume data and visualizing the features only. The development of new algorithms remains necessary because data sizes remain growing at a fast pace, and demands on processing capabilities are especially high in exploratory visualization, where the user wants to adjust application parameters and resource allocation in an online fashion. In such interactive data visualization, the speed of the data processing stage (data filtering, feature extraction, segmentation, etc.) should be comparable to that of the visualization step. Otherwise, the computational burden will render the overall technique ineffective and far from interactive.

Two important application areas are neuroimaging and bioinformatics. In functional neuroimaging, the goal is to detect significant changes in brain activity. Since these changes are small and distributed over the whole brain, and the images are noisy, the detection process is complex, requiring image processing to obtain high quality images, mathematical and statistical analysis for quantitative characterization of significant effects, and volume visualization for interpretation of the results. In particular, wavelets are applied for denoising the data in order to
enhance statistical power during the analysis of the data.

In bioinformatics, the group is involved in a research program aiming to reconstruct the cellular processes, metabolic potential (metabolome) and gene regulatory networks of selected organisms (gram-positive Bacteria and Archaea), by in-silico analysis of all proteins encoded by their chromosome. Research focuses on tools for simulation and interactive visualization of gene regulatory networks, based on knowledge from the scientific literature, information encoded in distributed databases, and experimental data. Also, evaluation of the effectiveness of visualization methods is part of this research effort.

Research in the area of computational geometry and object modeling focuses on the design of efficient, correct and robust algorithms for geometric problems arising in practical problems. This concerns representation, manipulation, reconstruction and visualization of curves and surfaces, as well as shape modelling of digital data. These problems often require non-trivial new concepts and techniques, based on a solid mathematical basis. Algorithms are being developed for fast rendering of implicit surfaces, the evolution of visible contours of various types of surfaces under camera motion and evolving geometric objects (morphing), and reconstruction of shapes from scattered data using Radial Basis Functions.

10.2 Overview of scientific results

Scientific visualization and morphological shape analysis

In the area of volume rendering, work on multiresolution representations for maximum intensity projection based on morphological pyramids was continued, with the aim to further improve approximation quality in higher levels of the pyramid. A new algorithm, called streaming MIP-splatting, was developed which resorts all detail coefficients in decreasing magnitude and projects only those coefficients needed to attain a user-defined accuracy. A multi-scale method based on mathematical morphology was developed which can be successfully used in segmentation, classification and object recognition tasks. The method is based on morphological hat-transform scale spaces and makes use of connected operators. The method was applied to classification of textures and object silhouettes, and also to automatic segmentation and identification of diatoms. Also, a novel, physically-motivated deformable model for shape recovery and segmentation was developed, called the Charged Particle Model. The model is based on a simulation of charged particles moving in an electric field. The flexibility and potential of the model was explored in a wide variety of settings: shape recovery, automatic segmentation and skele-
ton computation, see Fig. 6. The model has been extended to 3-D with promising results. We also are developing an alternative surface reconstruction method, using graphics hardware acceleration of the computations involved. Another issue is how to combine simple morphological transforms into a method for interactive segmentation which behaves analogously to mean-curvature flows widely employed by level-set methods.


Computational geometry and object modelling.

We continued our work on engineering robust and efficient software for geometric computing, in particular for non-linear surfaces in three-space. One of the results is a method for approximating and meshing of skin surfaces, used in molecular modeling. A distinctive feature of our approach is the guarantee of topological correctness of the output. Our algorithms compute a mesh or an approximation with the same topology as the skin surface. A crude mesh of low complexity, but with the correct topology, is further refined to obtain an arbitrarily accurate approximating mesh. See Figure 7 for an example. We used similar ideas for the certified computation of visibility features of smooth objects, like contours of surfaces under parallel or perspective projection.

In the area of Surface Modeling we obtained a new method for the evaluation of the Clough-Toucher $C^1$-interpolant of first order data over a triangular mesh. The algorithm saves a lot of computation steps as compared to earlier methods.

We also started a project on certified reconstruction of shapes from scattered data. The goal is to obtain a topologically correct reconstruction of a sampled object using a meshless approach via Radial Basis Function techniques. Some preliminary
results have been reported in Master’s theses on this topic. This research will be continued in two PhD projects starting in 2005.

A new method to solve small systems of polynomial equations has been devised and implemented. The method is a combination of algebraic geometry and combinatorial optimization. It is capable of solving small systems in an efficient and robust way. Using this method, a problem from computational geometry studied in the past and not solvable with conventional methods is solved in a stable way.

In the area of volumetric filtering and rendering, work on a Max-Tree-based data representation was continued. We have developed modifications and extensions of the Max-Tree data structure that enable visualization of filtered data directly from the Max-Tree without the need to reconstruct the volumetric data. Rendering is done either by direct volume rendering (splatting) or by an isosurface. The new method has shown to outperform marching cubes when changing the filter threshold interactively, and it was found that the method is competitive with interval trees for isosurface browsing. An example is given in Fig. 8.

Functional neuroimaging

Several approaches to wavelet analysis of functional magnetic resonance imaging (fMRI) data were developed. Wavelet-based denoising was found to introduce less smoothing, and to better retain the original shapes of active regions than the usual Gaussian smoothing method. Also, application of statistical parametric mapping with false discovery rate control on denoised simulated time series produced a smaller total number of errors than Gaussian smoothing or wavelet-based methods with a large smoothing effect (Wink and Roerdink, IEEE Trans. Med. Imaging 23 (3), pp. 374-387, 2004). A new method based on Fourier-wavelet regularized
deconvolution was developed to extract the haemodynamic response function from an fMRI time series. The algorithm only requires the assumptions of the general linear model and the separability of signal and noise in the frequency and wavelet domain. The assumption of Gaussian distributed noise in the fMRI signal was critically investigated. The best approach to get symmetric, nearly-Gaussian distributed noise, was shown to consist in subtracting a second time series from the time series that is analyzed.

**Gene network visualization**

A new multiple ontology visualization and exploration system was designed, based upon an existing open-source graph visualization framework. This framework supports several basic modules for input, graph management, transformations, metrics, layout, and interactive display, and allows for integrated network visualization of genomic, metabolic and proteomic information. A graph query language was developed that can search within a graph for certain (biologically relevant) sub-structures. A prototype application is now almost finished, and is used in biological case studies to demonstrate its functionality. A review study on graph visualization of biological networks has been carried out, with a focus on usability issues. Possible ways to take advantage of pre-existing open source software class libraries and frameworks in building extensible, flexible and scalable graph visualization systems are presented. A component of the SARAgene virtual reality framework for genomics visualization was subjected to a two-phase usability study encompassing both heuristics and formative evaluations. The results identify key user-interface requirements for graph-based virtual environments, and report on expert domain users opinions on the design of virtual environments for genomics and related fields. The Self-Organizing Map algorithm has been applied to the MINT protein-protein interaction database for *Bacillus subtilis* transcriptional regulation,
and has been implemented within the SARA\textgreek{ene} framework. This result will also be used for an initial evaluation study by biologists.

Software

The Matlab software for denoising fMRI time series developed by Wink in the project "Wavelet based methods for the analysis of fMRI time series" has been accepted as a plug-in of the SPM (Statistical Parametric Mapping) package, cf. http://www.fil.ion.ucl.ac.uk/spm/ext/#spm_wavelet

10.3 Research subjects

M. Ballan: functional neuro-imaging.
H. Bekker: shape similarity measure evaluation.
R. van den Berg: Multimodal perception and visualisation.
M. ten Caat: visualization of functional neuroimaging data; information visualisation.
A. Jalba: volumetric shape modelling, segmentation and visualization; graphics hardware computing.
N. Kruithof: computational geometry of evolving curves and surfaces.
S. Plantinga: visibility amidst smooth obstacles in the plane.
J.B.T.M. Roerdink: scientific visualization; morphological and wavelet-based multidimensional data processing; neuroimaging; bioinformatics.
G. Vegter: geometric computing and modelling; algorithms and schemes for curves, surfaces and manifolds; symbolic and numerical methods; visualization.
M.A. Westenberg: scientific visualization; neuroimaging.
Y. Zhan: surface modelling.

10.4 Publications

Dissertations

– A.C. Jalba, Automatic Image Segmentation and Analysis with Applications to Diatom Identification, promotor: J.B.T.M. Roerdink, Faculty of Mathemat-


**Articles in scientific journals**


**Articles in conference proceedings**


**Other publications**


10.5 External funding and collaboration

Vegter obtained, with Roerdink, an NWO-grant for a four year PhD-position on the project Certified Shape Reconstruction. The project will start early 2005.

Vegter is coordinator of the European project Algorithms for Complex Shapes (ACS), a joint venture of several European universities (FU-Berlin, University of Groningen, Max Planck Institut für Informatik at Saarbrücken, INRIA Sophia Antipolis, Tel Aviv University, National University of Athens and the ETH at Zürich). Its aims are engineering of robust and efficient software for geometric computing, study of objects beyond the usual linear geometric structures, and dissemination of knowledge and transfer of new technology in this area. This project will start on March 1, 2005.

External collaboration

Roerdink participates in the Groningen Neuroimaging Center of the local research school BCN (Behavioural, Cognitive and Neurosciences). In the area of Bioinformatics, he collaborates with the Department of Molecular Genetics (RUG) and groups from the Universities of Nijmegen and Wageningen. New research is currently initiated with the Brain Mapping Unit, University of Cambridge, on 3D visualisation of brain connectivity networks, and with the Kapteyn Astronomical Institute in Groningen on interactive feature extraction and visualisation of huge astronomical datasets.

Vegter collaborates with several groups in Europe, most notably with the Computational Geometry groups at INRIA Lorraine (Nancy, France), INRIA Sophia-Antipolis (France), the Ecole Nationale Supérieure in Paris and the Département de Mathématiques of the Université de Bourgogne (Dijon, France).

10.6 Further information

Roerdink is full professor of Scientific Visualization and Computer Graphics, and has a joint appointment with the Faculty of Medicine. He is on the editorial board of the Journal of Mathematical Imaging and Vision, associated editor of Pattern
Recognition, and Senior Member of the IEEE. He was reviewer for a large number of international journals and conferences in the area of computer imaging.

Vegter was appointed adjoint professor of Computational Geometry and Object Modeling on May 1, 2004. He is on the Program Board for Computer Sciences of the NWO-funded Lorentz Center in Leiden, The Netherlands.

Westenberg was a guest researcher with the Institute for Visualization and Interactive Systems (VIS), University of Stuttgart, Germany, from June 1 until July 31. In August 2004, he was awarded a Humboldt Research Fellowship by the Alexander von Humboldt Foundation, Germany. He will be with the VIS group until July 31, 2005.
11. **BioInformatics**

**Group leader:** Prof.dr. R.C. Jansen

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Tenure track (vacancy)

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<td>Dr. T.H. Reijmers</td>
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<td>Ir. J. Fu</td>
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<td>M. Dijkstra</td>
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1 In September 2004 the research group BioInformatics moved to the Groningen Biomolecular Sciences and Biotechnology Institute, another institute within the Faculty of Mathematics and Natural Sciences.
11.1 Research Program

Groningen Bioinformatics Centre (GBIC) was established in 2002, and new personnel started to arrive from March 2003 on. The research program of the GBIC concentrates on the development of novel analytical concepts, methods and models for the purpose of unravelling complex characters, fully exploiting GBIC’s strength in statistical and mathematical modeling and modern informatics. Its research is carried out in close collaboration with research institutes from both the Faculty of Medical Sciences and the Faculty of Mathematics and Natural Sciences. In September 2002 the BioGRID project started, funded by the EU, with specific tasks on information analysis and systems for GBIC, in collaboration with the faculty of Management Sciences. In 2003 new projects funded by NWO and Senter started, with tasks on statistical analysis of mouse gene expression (collaboration with dr G. de Haan), on bacteria microarray expression and protein localization (collaboration with prof Kuipers) and on proteomics (collaborations with prof Vonk and Bischoff). The collaborations give the GBIC-researchers access to hot and challenging research questions in bacterial, mouse and human genetics.

- Information Systems: Central to many of our activities is the MOLGENIS system, an information management system for local genomic laboratories. This system is now in place for bacterial research (Kuipers), and future developments will make it of use to new collaborators in plant, animal and human research. Research organizations need customizable, flexible and scalable information management. Within a fast developing domain paired to very specific local information applications you need your local information system to be quickly adaptable to suit changing needs. Interaction with your analysis tools should work right away without cumbersome import and export routines. The MOLGENIS project of GBIC offers such a system: a multi platform, web based Experiment Information System for local administration and management of microarray projects. A Biopartner grant has been obtained to set up spin-off activities.

- Genetical Genomics: Complex or ’multifactorial’ systems represent the frontier in biological and biomedical research. Clearly, genomics technologies offer great opportunities for studying complex systems at a depth never encountered before, but raise enormous challenges for bioinformatic processing of the vast amounts of heterogeneous data. This holds in particular once decreasing costs of technologies will allow for hundreds if not thousands of individuals to be analysed per experiment. We have recently outlined
the innovative concept of 'genetical genomics' (Trends in Genetics, 2001), which involves expression profiling and marker-based fingerprinting of each individual of a segregating population, and exploits all statistical tools used in genetic mapping (see also perspectives paper in Nature Reviews Genetics, 2003). By studying all genes in many different multifactorial combinations of alleles, genetical genomics is expected to be powerful and cost-efficient for unravelling metabolic, regulatory and developmental pathways. Although clear in concept, the bioinformatic techniques necessary to analyse such complex data are still left wanting. The research of GBIC aims at paving the path for reliable in-depth analysis of data from up-coming genetical genomics projects, and also aims at the development of improved strategies of multifactorially perturbing systems. GBIC will focus on (1) the design of new multifactorial strategies, (2) the improvement and validation of multifactorial models for quantitative expression variation, appropriately reflecting physical or biochemical functioning of genomic elements in well-studied cases, (3) the use of these models and the development of integrative multifactorial analysis approaches for 'hypothesis free' data mining in large-volume multifactorial experiments. A bridge between these projects will be formed by studying computer-simulated data and public/in-house data for various research models (particularly mouse). In 2003 we got access to mouse genetical genomics data through our collaboration with de Haan, and we made a start with the development of methods for (pre-) processing of the expression data (12,500 genes, 16-96 probes per gene, 30 mouse strains) and for managing and visualizing the results from the large amount of analyses. We collaborate in the frame of the international Complex Trait Consortium and together published two high impact papers in Nature Genetics and Nature Reviews Genetics.

- Medical Bioinformatics: the satellite group at the medical faculty develops novel statistical methods for haplotype-based gene mapping (HSS or Haplotype Sharting Statistics) in patient-control studies. Furthermore methods are under development for extracting relevant information from various types of gene expression data. The group also develops information infrastructure for high volume sequence analysis against in house and public databases.

### 11.2 Research subjects

**C.J. Albers**: Is interested in design and analysis of large-scale gene expression experiments with two-colour arrays in bacterial systems. Develops software for simulation of gene expression data.
**R. Alberts**: Studies methods for pre-processing of raw Affymetrix chip data and subsequent QTL analysis in genetic populations. Develops new statistical/bioinformatic methods as well as appropriate information infrastructure for handling the large amount of data and results.

**M. Dijkstra**: Studies methods for pre-processing and processing of complex proteomics data obtained via mass spectrometry (MS). Develops new statistical and bioinformatic methods for the detection of peaks in spectral data and for the detection of biomarker patterns in patient data.

**J. Fu**: Studies the design of gene expression experiments in a genetical genomics setting. Develops new quantitative genetical methods and computer simulation programmes.

**R.C. Jansen**: Is interested in statistically designing, modelling and analysing quantitative expression experiments on populations, using strategies that combine the merits of genetics with the power of genomics.

**S. Nyangoma**: Is interested in statistical methods and software for the analysis of large-scale gene expression analysis with Affymetrix chips, and for the analysis of large-scale mass-spectrometric data collected for proteins in plant, animal and human systems.

### 11.3 Publications

**Articles in scientific journals**


11.4 External funding and collaboration

External funding

- Jansen received a VICI-grant from the Netherlands Organisation for Scientific Research (NWO) for his research programme “Biointformatics for unravelling complex biological systems”. Jansen received kE 1.250 (kE 845 from NWO and kE 405 from the University of Groningen).

- Jansen obtained funding from the EC for a PhD student (Swertz) and senior scientist (de Brock) in the BioGRID project (RuG is financial coordinator)

- NWO-From Molecule to Cell project has been granted (Kuipers, Jansen)

- Senter funded two projects (Disorder detection in tropical products; Koudeafhankelijke rustdoorbreking bij bloembollen)

- RuG funded the project ’Genetics analysis of complex human diseases’ (breedtestategie, Navis, Jansen, et al.)

- The Dutch ’Regieorgaan’ Genomics coordinated called for a concerted action in the Netherlands on bioinformatics (BioASP) to be funded by a ICS/KIS grant. Groningen coordinated workpackages on information systems (de Brock), biostatistics (Jansen) and visualization (Roerdink)