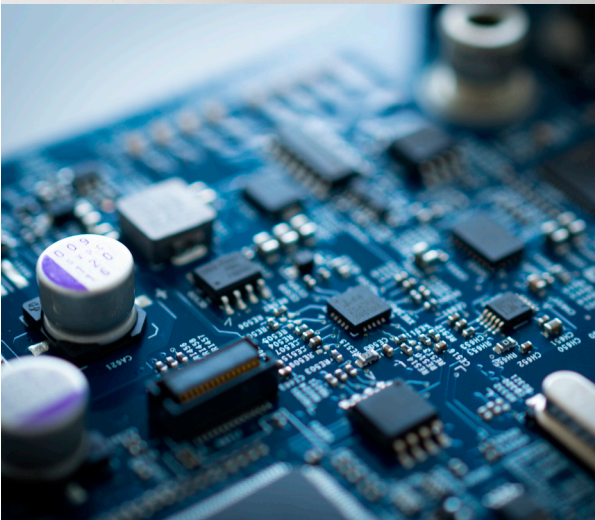


# In Control of Complexity

Linnaeus Research Environment LCCC 2008-2018 | LUND UNIVERSITY





## LCCC: Shaping Research Directions Across the World

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The Lund Center for Control of Complex Engineering Systems (LCCC) is a transdisciplinary and interdisciplinary research center focused on the sustainable and safe operation of large-scale technical systems. Research is pursued on a variety of applications, ranging from those in more traditional technological fields, such as robotics, energy supply and transportation, to less obvious ones, such as health care, communications and economics.

**The LCCC was founded in 2008**, and has been funded for the past ten years by the Swedish Research Council through a Linnaeus grant. The aim of Linnaeus funding is to increase the competitiveness of Swedish research in an international perspective.

**These ambitions** have been achieved at the LCCC by:

- ▶ actively recruiting and increasing the competence of those working at the LCCC,

- ▶ regularly inviting international guests and organizing workshops and so-called Focus Periods – guest programs designed to stimulate new directions of research in the international community,

- ▶ supporting new, innovative collaborations through seed money, and

- ▶ continuously exchanging knowledge and sharing experience with industry.

**This brochure** presents a popular scientific summary of the achievements of the LCCC as a Linnaeus Research Environment during the 10-year period from 2008 to 2018.

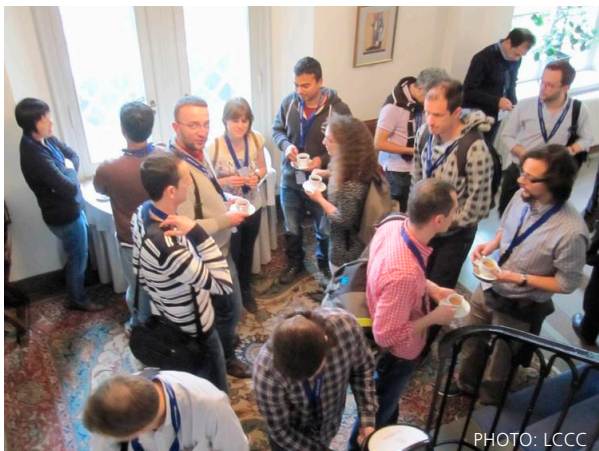
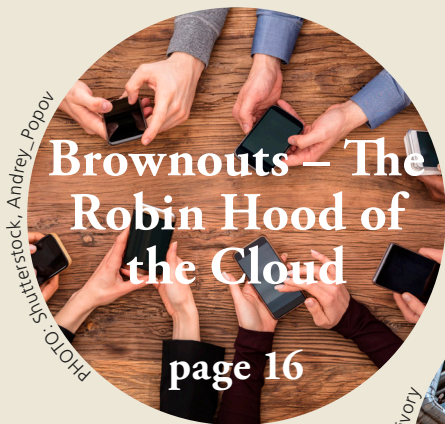
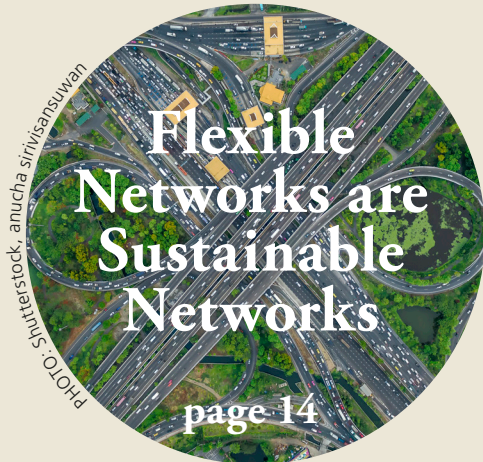


PHOTO: LCCC

” ...bringing the top researchers together and, as a result, shaping research directions across the world.

**Tryphon Georgiou**

Professor at the Department of Mechanical and Aerospace Engineering, University of California, Irvine, USA



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## AUTOMATIC CONTROL – THE HIDDEN TECHNOLOGY

Automatic control is all around us, although we hardly ever notice it. It is a wide generic term used to describe the various control systems in everyday things – ranging from the thermostat controlling our central heating, and the steering and stabilization of cars and ships, to large industrial control systems with tens of thousands of input control signals and output measurements – all with little or no human intervention.

The heart of automatic control is a regulator, and usually some form of feedback. Constructing an efficient and reliable regulator requires knowledge on the system in question and its characteristics. The complexity of the regulator can range from a simple on-off switch to multivariable high-level algorithms.



**2013**  
 Laurent Lessard receives the Hugo Schuck Best Paper Award, given to the best paper presented at the American Control Conference, and Pontus Giselsson is one of the finalists in the Best Student Paper Award.

- 2011 Workshops**
- ▶ Dynamics, Control and Pricing in Power Systems
  - ▶ Control of Computing Systems

- 2012 Workshops**
- ▶ Robotic Skill Learning and Cognition
  - ▶ Second LCCC Industrial Workshop
  - ▶ System Design Meets Equation-based Languages
  - ▶ Information and Control in Networks

- 2009 Workshop**
- ▶ First LCCC Industrial/Academic Workshop

- 2015 Workshop**
- ▶ Model-Based Engineering

2008

**2011**  
 Giacomo Como, previously at MIT, is recruited as an assistant professor.

- 2013 Workshop**
- ▶ Formal Verification of Embedded Control Systems

- 2014 Workshops**
- ▶ Energy Management and Control in Buildings
  - ▶ Cloud Control
  - ▶ Dynamics and Control in Networks

- 2010 Workshops**
- ▶ Multi-Agent Coordination and Estimation
  - ▶ Distributed Decisions via Games and Price Mechanisms
  - ▶ Adaptation and Learning in Autonomous Systems
  - ▶ Distributed Model Predictive Control and Supply Chains

**2013**  
 Johan Åkesson is now employed by the innovation company Modelon, and the responsibility for the development of JModelica.org has been transferred from the Department of Automatic Control to Modelon.

**2014**  
 Martina Maggio, formerly at Polytechnic University of Milan, Italy, is employed as an assistant professor.

# Ten Years of the LCCC

During the past ten years, the LCCC has hosted 11 Focus Periods and 18 workshops. These events were designed to stimulate new research directions in the international community and have been important for the dissemination of research results, but also to increase the visibility of the LCCC, and increase its attractiveness for international recruitment.

**2015**  
LCCC, together with two other Linnaeus environments, CADICS and ACCESS, becomes a foundation for the Wallenberg AI, Autonomous Systems and Software Program (WASP), Sweden's largest ever individual research program.

**2016 Workshop**  
▶ Process Control



On page 20:  
Six Questions to the LCCC Board

**2015**  
Pontus Giselsson is employed as an assistant professor, after a postdoc at Stanford University, USA.

**2017 Workshop**  
▶ Large-Scale and Distributed Optimization





PHOTO: LCCC

## Academia to Academia

**New ideas have been born**, and exciting approaches brought to fruition by combining scientific expertise in automatic control and electrical and information technology with that from other disciplines. The state of the art has been advanced – within engineering, as well as medical and social applications – by the implementation of both qualitative and quantitative approaches. More than 1 100 scientific articles were published during the ten years that the center has existed.

## Country to Country

**More than 500 researchers**, originating from over 30 countries and six continents, have visited the LCCC between 2008 and 2018. New international collaborations, significantly improved contact networks for young researchers, and the recognition of the LCCC as an internationally leading center within control of complex engineering systems are just some of the outcomes.



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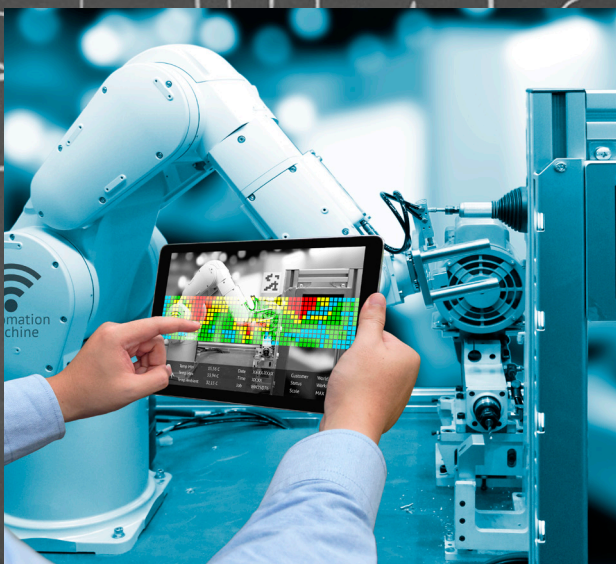


PHOTO: Shutterstock, Zapp2Photo

## Academia to Industry

**One of the primary aims** of the LCCC was to promote cooperation with industry. This has resulted in numerous successful collaborations, ranging from those with small university spin-offs to international giants such as Spotify, giving researchers access to challenging industrial environments and the opportunity to transform research into commercial use.

show that if no  $P > 0$  satisfies  $(*)$  then  
there exists periodic  $\left\{ (w(t), x(t)) \right\}_{t=0}^{t=T-1}$   
satisfying  $(**)$  and (3).

”

The research centre  
has a synergistic  
effect. The selection  
of research interests is  
multi-disciplinary and  
balanced. Very effective  
collaborations have been  
set up at the national  
and international level.

From:  
Midterm Evaluation Report of the 2008  
Linnaeus Centres

PHOTO: LGCC



PHOTO: Private

## ” ... time to spark collaborations ...

### **Tryphon Georgiou**

Professor at the Department of Mechanical and Aerospace Engineering, University of California, Irvine, USA

**“Over the years,** I have participated in three different Focus Periods: Multi-Agent Coordination and Estimation (in February of 2010), Dynamics and Control in Networks (in October 2014) and Large-Scale and Distributed Optimization (in June 2017). The theme of each of these Focus Periods, as well as other Focus Periods at the LCCC, has been timely and impactful in control science and engineering by virtue of bringing the top researchers together and, as a result, shaping research directions across the world. Each time, I stayed for a few weeks and I enjoyed the close interaction with others; I exchanged ideas that certainly shaped my views and subsequent work.

**“The design of the Focus Periods,** with periods of concentration, lectures, social interactions, etc., was ideal and also helped forge professional relations. The time allocated for interactions, between periods of concentrated work, provided opportunities for useful exchanges and time to spark col-

laborations (I certainly started some) as well as opportunities to build friendships between researchers and groups. The facilities, including accommodation, and most importantly, help from the staff, were absolutely superb! Overall, it was a model program.

**“In 2016,** I organized a research program at the Institute of Mathematics and its Applications (IMA), at the University of Minnesota in Minneapolis, USA, on the subject of Control. I borrowed many of the insights I gained from the LCCC, and tapped onto the connections forged during my visits to Lund, when deciding on the structure of the IMA program and the list of participants.

**“In conclusion,** I believe that the value of the LCCC to the academic community has been immense. I truly hope that an analogous structure will succeed the LCCC at Lund soon, and that it will continue along similar lines in the future.”







PHOTO: Private

## ” ... the workshop gave excellent networking opportunities.

**Margret Bauer**

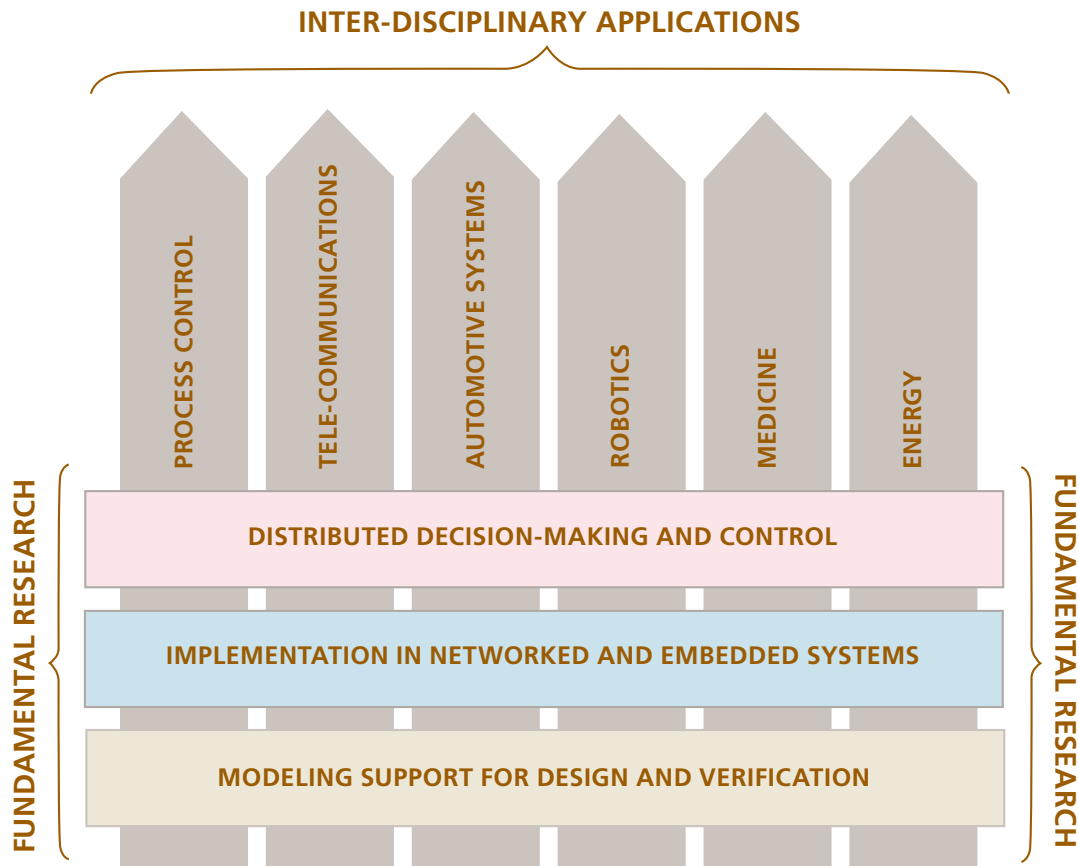
Extraordinary Professor at the Department of Electrical, Electronic and Computer Engineering, University of Pretoria, South Africa

**“I have visited the LCCC twice**, once for a workshop on Process Control and once as the examiner for a PhD defense. The Department of Automatic Control at Lund, and the groups of Tore Hägglund and Karl Johan Åström were well known to me even before my visits. I had encountered their work during my PhD studies, and always admired the seemingly effortless and elegant algorithms developed in Lund, which tackle the most pressing industrial research questions.

**“The workshop** that I attended provided an excellent platform for discussions on the latest trends in automation. Having worked at ABB for about ten years, I was very familiar with the international viewpoints and research directions, but it was an eye-opening experience to compare these with the developments at Schneider and Exxon Mobil, in addition to those of colleagues from academia. Being able to meet Tore Hägglund and Karl Johan Åström in person, and hear their thoughts and opinions on my research, added yet another

dimension to my visit. I was very encouraged to hear a talk by Karl Johan Åström about his research career, where he said ‘Industry is my laboratory’.

**“From a personal point of view**, the workshop gave excellent networking opportunities. During the months before the workshop, my South African colleagues and I were organizing the first African Control Conference, an IFAC (International Federation of Automation and Control) co-sponsored event. I mentioned the difficulties we had in raising funds to sponsor other African colleagues from outside South Africa to come to our event to Daniel Rivera, a co-presenter from Arizona State University. He alerted me to the IEEE (Institute of Electrical and Electronics Engineers) Outreach Fund of the Control Systems Society, which he administers. Our application was successful and we were able to obtain funding for 15 control engineers from 10 different African countries to attend the conference in Johannesburg.”



## From Algorithm to Application

The vision of the LCCC during the ten years of Linnaeus funding was to create and maintain a world-leading center for research on the control of complex engineering systems. Although the LCCC has mainly pursued fundamental research, many of the research efforts have been inspired by different applications, and the transfer of ideas and methodology between different scientific fields has been central.

**The research carried out** at the LCCC can be divided into three different areas of fundamental research, and six areas of interdisciplinary application, as shown above. Research has been pursued within the vertical and horizontal blocks, as well as the intersections. The areas of fundamental research have been led by LCCC faculty members, with competence within automatic control, mathematics and computer engineering, as well as communications. Most of the PhD projects have been performed within the areas of fundamental research. However, they have usually also had an application component, involving industrial partners or colleagues from other disciplines; allowing fundamental research to be inspired by applications, without the results being specific to any particular application.

” *The LCCC has always promoted application-driven basic research.*

**Johan Åkesson**

Chief Technology Officer of the innovation company Modelon, Sweden

# From Seeds to Success

Apart from traditional research, significant efforts have been devoted to so-called seed projects. The LCCC has supported six different seed projects during the ten years of Linnaeus funding by providing two years of initial funding to a number of new research directions.

**The idea was** to provide funding to research ideas that may not yet have reached the degree of scientific maturity necessary for external funding, and was suggested by the LCCC's International Advisory Board.

**Charlotta Johnsson** is a professor at the Department of Automatic Control and member of the LCCC Board.

– Combining exciting new research ideas and competent people you can peak. It was definitely worth the investment. Several of the projects have been really successful, she says. Among them were medical applications, such as the automatic regulation of anesthesia in surgeries (see next page), and biological ones, such as the optimization of the fermentation of the bacterium *Bacillus licheniformis*. The fermentation project is now being run by the Danish-based company Novozymes, a world-leader in biological solutions.

” *Combining exciting new research ideas and competent people you can peak. It was definitely worth the investment.*

**Charlotta Johnsson**

Professor at the Department of Automatic Control at Lund University, Sweden



PHOTO: Shutterstock, Master Video

## THE SIX SEED PROJECTS

- ▶ Surgical Robotics
- ▶ Cerebellar Control and Adaptation
- ▶ Anesthesia in Closed Loop
- ▶ Process Control and Information Handling
- ▶ Dynamics, Pricing and Control in Power Systems
- ▶ Optimizing Fermentation Control for *B. licheniformis*

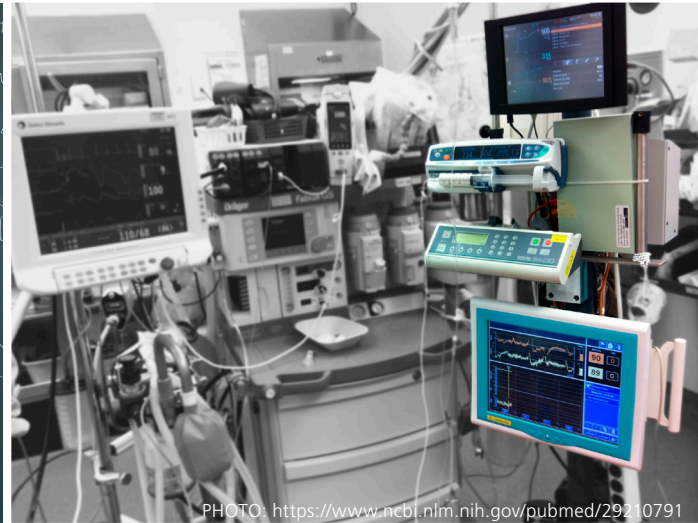
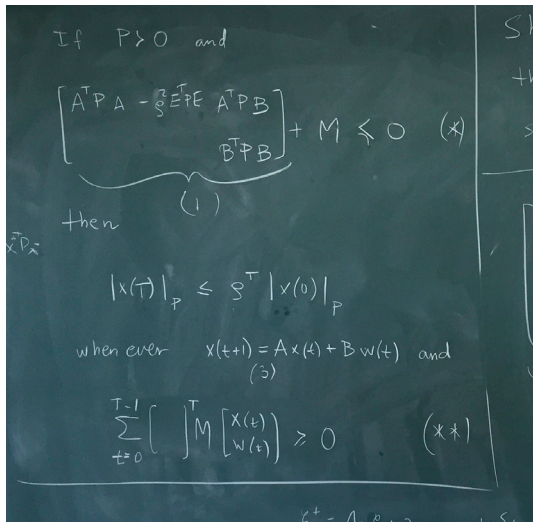


PHOTO: <https://www.ncbi.nlm.nih.gov/pubmed/29210791>

## From Seed to Serious Funding

When Kristian Soltesz, currently a researcher at the Department of Automatic Control, was a PhD student, he went to Canada to carry out a project on the automatic control of paper mills.

– When I arrived, the professor asked me if I would consider working on medical applications instead, such as the anesthesia of patients during surgery. A strong team of engineers, doctors and research assistants at the University of British Columbia (UBC) and the British Columbia Children’s Hospital convinced Kristian Soltesz, so he applied for seed money from LCCC, and got it.

**The aim of Kristian Soltesz’** seed project was to automate the control of anesthesia normally provided by the anesthesiologist. Anesthesia is currently administered to patients completely manually. The anesthesiologist assesses the anesthetic state of the patient using clinical monitoring, for example, heart rate and blood pressure, as well as patient signs, such as response to speech, eyelash reflex and breathing pattern, and adjusts the dosage accordingly. Kristian Soltesz and his colleagues wanted to create models that could be used in the development of computerized algorithms.

– Researchers at UBC had already developed sensors to measure the brain activity of patients, which is correlated to their degree of consciousness, says Kristian Soltesz and continues:  
– My task was to develop mathematical models for the administration of anesthetic drugs before and during surgery, where the drug infusion rate is continuously adjusted depending on the response of the individual patient.

**In their first study,** they investigated the effect of automatic closed-loop control of anesthesia on 102 children aged 6-17 years undergoing endoscopic investigations.

– It was a success. Our system achieved and maintained an adequate degree of anesthesia in 85 percent of the patients, which shows that it is possible to control anesthesia in children using a rather simple controller and minimal intervention, says Kristian Soltesz.

Numerous clinical studies and a multitude of publications have since proven the method to be both robust and safe, enabling the anesthesiologist to simultaneously supervise more patients. Even more importantly, drug dosage is expected to decrease, and post-operative recovery to be faster, as the patients are monitored more closely, and drug doses better adjusted.

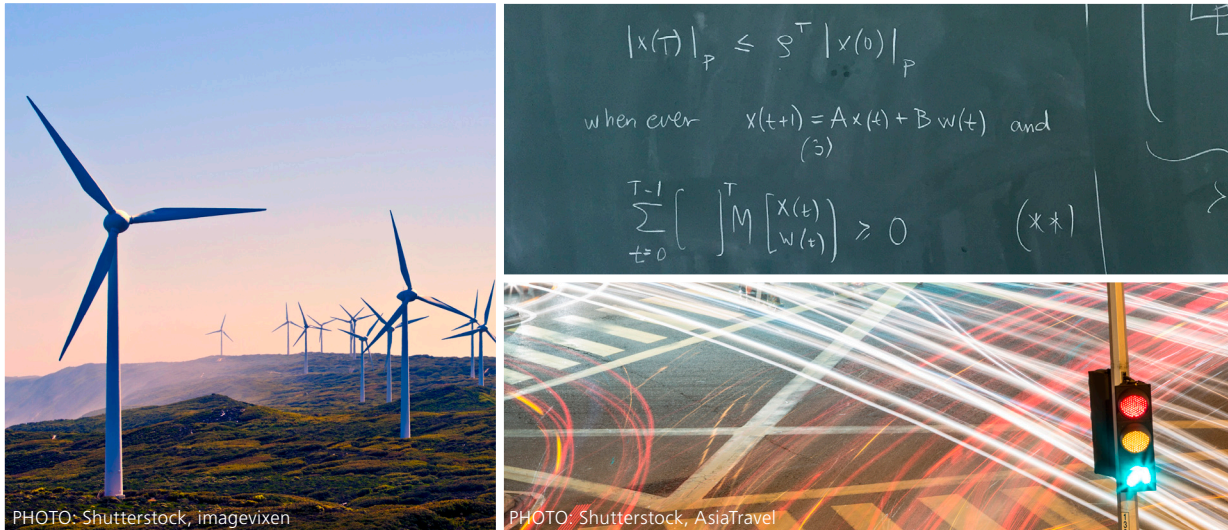
**Closed-loop-controlled anesthesia** is now awaiting approval from agencies such as the US Food and Drug Administration.

– Getting seed money to start this project has been invaluable to me. My PhD thesis is largely based on the research performed during the two years funded by seed money, and it has been decisive in my current research in organ preservation, says Kristian Soltesz, who now has no problem obtaining financing from other sources.

” *Getting seed money to start this project has been invaluable to me.*

**Kristian Soltesz**

Researcher at the Department of Automatic Control at Lund University, Sweden



# Flexible Networks are Sustainable Networks

The advantages and disadvantages of centralization and decentralization are themes commonly discussed in both politics and organization leadership. However, these concepts are also highly relevant within the field of engineering. By studying large-scale networks, such as traffic systems and wind power parks, LCCC researchers have proven global optimality using only local information, generating more efficient as well as more resilient networks with less environmental impact.

**Giacomo Como** is an associate professor at the Department of Automatic Control at Lund University and a member of the LCCC Board.

– It may seem somewhat surprising that local information can give global optimality, but it is a recurring theme within this type of research, he says.

By moving away from the traditional control paradigm of a centralized architecture in which all the information is collected in a single control unit, where it is processed, and the response determined, towards a decentralized architecture with local control units, LCCC researchers have designed more flexible and resilient network systems that are less prone to large-scale disruptions. This is an important finding for traffic networks in particular.

– We have reached a situation where the capacity of our infrastructure is very limited. The traffic load is increasing continuously, but there is not enough space or money to meet these demands in terms of newer or wider roads.

The consequences? People are sitting in queues for hours and hours every day, and, sometimes, massive traffic jams occur.

**An extreme example** is the China national highway 110 traffic jam in 2010, causing congestion of thousands of vehicles for more than 100 kilometers, and lasting for more than ten days.

– The resilience of a system can be improved using control techniques to design traffic systems with smart functions, avoiding this kind of massive congestion in the future, saving both time and money, as well as reducing pollution, says Giacomo Como. These smart functions include variable speed limits, ramp metering (i.e. limiting the number of vehicles that are allowed to enter a freeway at a particular time), dynamic traffic lights, and routing choices such as prescribed turning ratios at junctions (through navigation support in vehicles). Both tolls and incentives have been tested in several parts of the world, with the aim of routing traffic more efficiently.

**Giacomo Como and his colleagues** have also adopted another significant shift in their approach to large-scale networks.

– Static models have long been regarded as the fundamental design paradigm for infrastructure systems, and represent an

important area of mathematical programming. But there is increasing awareness that the full potential of large-scale systems can only be properly understood in a dynamical context, says Giacomo Como, and continues:

– Using dynamic models, we are trying to design control parameters that make traffic networks more resilient, and reduce the effects of shocks that inevitably occur in a system, instead of leading to serious problems.

**Dynamic modeling** of large networks is one of the major trends in control theory today, not only in traffic systems, but also, for example, in financial and social systems. The research carried out on resilient network dynamics at the LCCC has received significant international recognition, and, in 2015, Giacomo Como and his colleagues were awarded the George S. Axelby Outstanding Paper Award, for their work on distributed routing in dynamical networks.

– We introduced the concept of ‘the margin of resilience’, which is a way of measuring how resilient different controls are in different types of networks, says Giacomo Como.

**In order to test** their dynamic models, Giacomo Como and his colleagues at the LCCC are collaborating with research groups in both Central Europe and the USA, where traffic networks are considerably larger, and the traffic more intense than in Sweden. Giacomo Como believes that the area of transportation provides many opportunities for future research.

– Everyone is talking about self-driven smart cars nowadays. Just imagine all the control issues that will emerge in the co-existence between self-driven cars and traditional means of transportation, which will definitely be around for a long time to come. I believe many of our future research challenges will be in the interaction between the two, says Giacomo Como.

” *Just imagine all the control issues that will emerge in the co-existence between self-driven cars and traditional means of transportation...*

**Giacomo Como**

Associate professor at the Department of Automatic Control at Lund University, Sweden

## DISTRIBUTED DECISION-MAKING AND CONTROL

**Despite the fact** that many industrial applications already rely on distributed control structures, little research has been carried out on the theory and methodology of the design and verification of these distributed controllers. The purpose of the LCCC research area Distributed Decision-making and Control was to meet this demand for research, and answer the question, “How do we design and control networks so that they operate in the most efficient way possible?”.

**The networks studied** have ranged from traditional engineering systems, such as traffic systems and wind power parks, to networks of social, economic, and medical character.

**The research** carried out within Distributed Decision-making and Control has received a number of awards.

**Research fields** included in Distributed Decision-making and Control:

### DISTRIBUTED CONTROL USING PRICE MECHANISMS

Solves optimization problems in various engineering applications iteratively through price negotiations between subsystems, based on the idea of using price mechanisms for coordination of large-scale systems.

### FUNDAMENTAL LIMITATIONS IN CONTROL SYSTEMS WITH DISTRIBUTED INFORMATION

Examines emerging theories for control within a distributed framework, in contrast to the traditional approach of developing theory for multivariable control in a centralized setting.

### CONTROL OF TRAFFIC NETWORKS AND OTHER MONOTONE SYSTEMS

Investigates the performance and robustness of traffic networks, and how the methods used within these networks can be transferred to other types of systems.

### LOW-RANK DISTRIBUTED CONTROL

Investigates optimal resource allocation and the exchange of information within multi-agent applications such as wind farms, in order to increase the resilience of the system.

### BENEFITS FROM SYMMETRY IN ROBUST CONTROL

Examines the advantages of symmetry in robust control for both synthesis and distributed control purposes.



PHOTO: Shutterstock, Maksim Kabakou

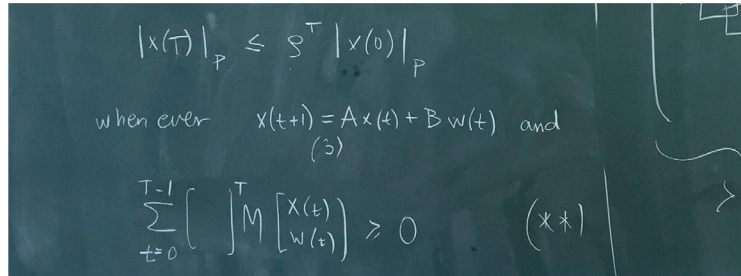


PHOTO: Shutterstock, GaudiLab

# Brownouts – The Robin Hood of the Cloud

Using the concept of brownouts, i.e. supplying a little less to everyone, in order not to cut off some users completely, researchers at the LCCC have developed a new approach to handling dynamic resource capacity issues in cloud computing – which has attracted the interest of several web giants.

**Cloud computing** is expected to become one of the main technologies driving the future economy. However, variability in the number of users, with unexpected peaks in the volume of requests, for example, during natural disasters or upon the death of celebrities, as well as unexpected hardware failures, requires costly hardware over-provisioning for many companies providing cloud computing services. Martina Maggio, associate professor at the Department of Automatic Control at Lund University, and her colleagues working on cloud computing at the LCCC, have developed a solution to the problem.

– Given the often relatively short duration of the peaks, we suggest that it is more profitable to temporarily downgrade user experience rather than to continuously increase server capacity. We call it the ‘brownout paradigm’.

**The concept of brownouts** comes from the power industry, where intentional voltage drops are often used to prevent blackouts in the case of emergencies. In such a situation, incandescent light bulbs dim – emitting less light and consuming less power – hence the term brownout.

– The same basic principle can be applied to cloud computing. By deciding which functions are mandatory and which are optional, you can turn off the optional ones when user workload increases or server capacity goes down.

**Martina Maggio uses an online shop** as an example. The mandatory function is providing information on what the user wants to buy. Advertising and recommendations are of course preferable, since they increase user experience as well as owner revenue, but they are not necessary. By disabling the optional functions and replacing them with images requiring no computing capacity at all, all the users can be served within a reasonable time frame, and no one will be cut off completely in the case of capacity shortages.

## CLOUD COMPUTING

Cloud computing provides a simple way to access servers, storage, databases and a broad set of application services over the internet. A cloud services platform, such as Amazon Web Services, owns and maintains the network-connected hardware required for the application services, while users provision and use what they need via a web application (instead of locally on their own computer). It can be compared to the water supplied by the utility company – it simply works without the user having to be concerned with the underlying infrastructure. The best thing? You only have to pay for what you use.



**This concept was tested** on two different e-commerce applications. The result?

– We were able to make the applications brownout-compliant with less than 170 lines of code, and improve the capacity of software applications to withstand flash crowds and hardware failures, says Martina Maggio.

However, the brownout concept is not limited to e-commerce applications.

– It's applicable to many different systems, apart from online shopping, for example, online newspapers and search engines. The only thing you really have to do is to decide which functions of your system are mandatory and which are not.

And then add the optional code, which can be dynamically deactivated through decisions based on control theory – all automatic of course, reducing the maintenance required for the system.

**The 170 lines of code** developed by the researchers at the LCCC are now freely available on the web. Several web giants have contacted the researchers to discuss the concept.

– They all have similar ways of avoiding overload, but not exactly the same as our concept, says Martina Maggio.

And it definitely isn't free.

– For us it was never a matter of money. We like being open and giving people the possibility to use simple but smart solutions like this one.

Another important incentive for the researchers was energy efficiency.

– Having high spare capacity to handle occasional peaks requires a lot of energy. There have been complaints about the energy intensity of large data centers, particularly as reducing our energy consumption is now an important issue. Employing our concept, or concepts similar to ours, will make the spare capacity of large data centers redundant.

**Martina Maggio has now** moved on to improving other systems, among them surveillance camera and security systems. But what she really wants to do is to inform people about what a powerful tool automatic control can be.

– Automatic control is everywhere around us, but most people are not aware of it. Control theory can be extremely useful, and I am eager to show people how easily it can be used to improve systems and increase their efficiency.

” *Automatic control is everywhere around us, but most people are not aware of it.*

**Martina Maggio**

Associate professor at the Department of Automatic Control at Lund University

## IMPLEMENTATION IN NETWORKED AND EMBEDDED SYSTEMS

**Today**, many engineering systems are both embedded and networked, which means that they have a complex structure as well as distributed functionalities. In order to allocate the physical resources within such a system, a resource-aware design is necessary, which takes into account the efficiency of the separate parts, as well as the whole system.

**Important parts** of the research within Networked and Embedded Systems at the LCCC have been to identify methods for static as well as dynamic allocation of physical resources in systems, to design and optimize resource-aware control mechanisms for these systems, and to develop reliable performance estimation methods. Significant attention has been devoted, in particular, to dynamic approaches, with adaptive resource management, and more holistic approaches, where the interaction between the computing system and its environment is taken into account.

**Research fields** included in Implementation in Networked and Embedded Systems:

### CLOUD CONTROL

Proposes a control-theoretical approach to a range of cloud management problems, with the aim of transforming static, energy-consuming cloud data centers into self-managed, dynamic, dependable infrastructures, which constantly deliver the expected quality of service at acceptable operation costs and carbon footprint.

### ADAPTIVE RESOURCE MANAGEMENT FOR EMBEDDED SYSTEMS

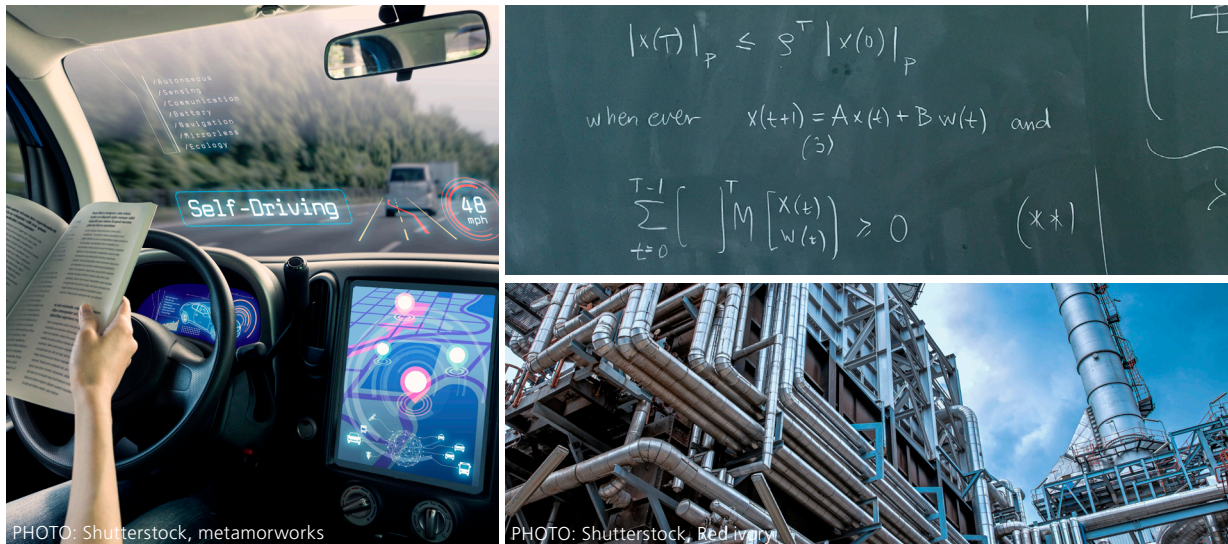
Uses dynamic allocation of resources, based on measurements of resource consumption, resource availability, and quality of service, as a new, alternative approach to the traditional static approach to resource management.

### EVENT-BASED CONTROL

Develops theory and methodology for event-based state estimation and the control of networks, with the aim of reducing state variance and the number of network transmissions.

### CONTROL OF COORDINATED MULTIPOINT COMMUNICATION SYSTEMS USING LOCALIZATION-BASED PREDICTION

Uses localization-based information from GPS together with mobile sensors to improve the efficiency and bandwidth of large-scale communication systems.



## Modelica Makes Systems Talk

Have you ever heard of model-based engineering? Johan Åkesson, previously a researcher at the Department of Automatic Control, and currently Chief Technology Officer at the innovation company Modelon, knows all about it. By combining simulation with optimization, he has created a completely new tool kit and contributed to the expansion of Modelon from a small university spin-off to a worldwide player, with customers such as the ANSYS Group and Siemens.

**The ideas of the language** behind the success, Modelica, were originally developed at the Department of Automatic Control already in the 1970s. However, due to limited computing capacity, this research direction was discontinued. A second development phase took place in the 1990s, but it was not until Johan Åkesson started his PhD studies during the 2000s that research on the language Modelica gained real momentum.

– Using Modelica, one can build mathematical models of industrial systems in order to simulate and improve various physical processes, says Johan Åkesson.

**Modelica** is a so-called modeling language. In contrast to a general-purpose language, which requires substantial programming skills and effort to achieve a certain outcome, a modeling language offers engineers the possibility to express physics in an intuitive way, for example, through mathematical equations and relations between physical objects. Extensive standard libraries for mechanical, electrical and thermal models, for example, facilitate the modeling process, enabling the engineer to construct models of complex systems relatively quickly, making Modelica suitable for a wide range of industrial systems. The ultimate goal is more efficient product design processes with minimal waste.

**Apart from re-establishing** research on Modelica at the Department of Automatic Control, Johan Åkesson also added an optimization module to the language.

– Both simulation and optimization have been around for a long time. What I did was simply to combine the two in order to get a more efficient tool that can tell you not only what happens if you change something, but also how you can achieve a goal in the most efficient way possible.

He uses a robot that has to move from point A to point B as an example. The robot should not only move from A to B, but it should do so in the most efficient way possible – a typical example of an optimization problem.

– Cooperating with researchers from other departments at the University, who had other skills than mine, meant that the additions to Modelica became very powerful very quickly, says Johan Åkesson.

**Networking** has always been one of Johan Åkesson's strong points. This could have been one of the reasons he was asked to lead one of LCCC's fundamental research areas, "Modeling Support for Design and Verification", just after obtaining his doctorate.

– It was an amazing opportunity for me to get to lead a research group at such an early stage in my career. I was, and I still am, very proud of it.

Building strong, competitive and creative teams is still something that interests him, but now he is doing this at Modelon instead of at the University. The move from the academic world to the business sector came gradually, largely through the goodwill and ambition of the LCCC to create strong cooperation with industry.

– The LCCC has always promoted application-driven basic research. Modelon would not be where it is today if it were not for the research performed within the LCCC. Many of our software developers are working on research emanating from the LCCC, says Johan Åkesson.

**JModelica.org**, as the Modelica implementation that also supports the optimization extension is called, is today an open source platform, maintained by Modelon in collaboration with the Department of Automatic Control, while the so-called OPTIMICA Compiler Toolkit is a commercial product marketed by Modelon. This provides an excellent example of how the combination of basic and applied research and collaboration between academia and businesses can be fruitful for everyone, according to Johan Åkesson.

– For me personally, it has been wonderful. I was able to continue the research I started as a PhD student at university, provide it freely as an open source, and then develop it into a commercial product at Modelon, he says.

**Modelon currently has** offices in North America, Europe, and Asia. Modelica is used in the automotive, aerospace and power industries, as well as in industrial machines and building systems.

– The full potential of Modelica is far from being realized. We have a lot of work ahead of us in promoting Modelica as an efficient engineering platform. I believe it all starts in academia, says Johan Åkesson and continues:

– If students, who are our future engineers, realize the potential of model-based engineering, it will eventually permeate the industrial world, saving many companies a lot of money, as model-based engineering is so much more cost-efficient than building prototypes and performing practical experiments.

It is not for nothing that the cooperation between the Department of Automatic Control and Modelon has been called ‘the Master’s thesis factory’.

” *Many of our software developers are working on research emanating from the LCCC.*

**Johan Åkesson**

Chief Technology Officer of Modelon, Sweden

## MODELING SUPPORT FOR DESIGN AND VERIFICATION

**Industrial control** design processes are increasingly making use of complex large-scale heterogeneous models, often encoded using high-level modeling languages. Although many simulation tools offer reliable predictions of system behavior, a remaining key-challenge is real-time simulation, i.e. simulations where the computer model runs at the same rate as the actual physical system. Real-time simulation is often used for hardware-in-the-loop simulations, a technique used in the development and testing of complex, real-time embedded systems such as those used in industrial systems.

**The aim** of the research within Modeling Support for Design and Verification is to create a methodology, computer languages, standards, and tools for the design and verification of these complex engineering systems. The challenges are twofold:

- 1) to bridge the gap between mathematical theories and engineering practices, and
- 2) to bridge the gap between language descriptions and state-of-the-art symbolic and numerical algorithms, in order to increase the flexibility and extensibility of current languages and tools, thus generating models with wider applicability.

**The research** within Modeling Support for Design and Verification has been partly performed in cooperation with industry.

**Research fields** included in Modeling Support for Design and Verification:

### SOLUTION TECHNIQUES FOR LARGE-SCALE DYNAMIC OPTIMIZATION

Explores various techniques for analyzing and exploiting large-scale differential algebraic systems, resulting from object-oriented physical models.

### DYNAMIC OPTIMIZATION ALGORITHMS FOR PARALLEL ARCHITECTURES

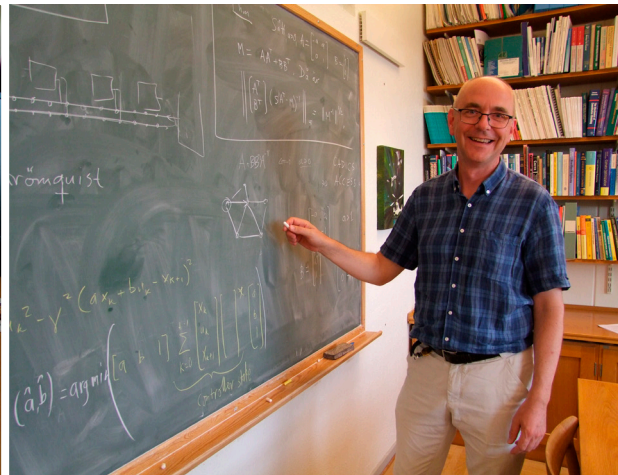
Develops new algorithms to explore new hardware architectures such as those of modern processors, where the number of cores is increasing rapidly, while clock frequencies are not.

### CO-SIMULATION OF PHYSICAL SYSTEMS

Studies the exchange of information between coupled dynamic models, where each model contains not only a model equation, but also an integration algorithm.



PHOTOS: Ulrika Jönsson Belyazid



## Six Questions about the LCCC

Three questions to Charlotta Johnsson, professor at the Department of Automatic Control and member of the LCCC Board between 2008 and 2018 (Vice Coordinator 2008-2013), and to Anders Rantzer, professor at the Department of Automatic Control and Chair of the LCCC Board between 2008 and 2018.

### 1 What is the first thing that comes to mind when thinking about the LCCC?

– All the people who have contributed. And stability. The LCCC have had a substantial amount of money to spend each year, which has given us the possibility to realize projects and activities that would otherwise not have been possible.

### 2 What significance did the Linnaeus grant have for the possibility to promote the research performed at the Department of Automatic Control in an international perspective?

– The Linnaeus grant enabled us to host several Focus Periods, and we were able to invite well-known senior researchers who would otherwise most likely not have come. I believe these Focus Periods have been extremely important in placing us on the map in an international context, and for our researchers to meet and network with people they would otherwise not have met.

### 3 The gender distribution has changed considerably at the Department of Automatic Control during the past ten years. What do you think about that?

– It is very gratifying that there are so many more women now than when the LCCC started. I see this as a positive result of the Linnaeus funding. Gender balance is always included in our discussions on, for example, new appointments, and we have a group working on gender equality and equal opportunities. We actively try to identify qualified female students and encourage them to apply for our PhD positions.

### 1 How would you describe the research performed during these ten years?

– Automatic control has a long history at Lund University, but what has been new and very exciting about the LCCC is the initiation of connections with other disciplines, such as biology, medicine, economics and the social sciences. These connections have developed during the past ten years, and have enriched us by triggering new types of questions – ones that have not been asked before, at least within our discipline.

### 2 What has the LCCC meant for you personally, and for your research?

– It has definitely widened my perspectives. The interdisciplinary and transdisciplinary approaches have led me to reformulate many of my research questions and to re-evaluate research results. Also, new and fascinating research themes can be identified when transferring ideas from one field to another.

### 3 How will LCCC live on when the Linnaeus grant ceases?

– The Linnaeus center as a concept will cease to exist, but the research will continue with a similar constellation of people. We will continue building on the methods and ideas that were established over the past ten years, and several projects will be a natural continuation of the LCCC, among them the Wallenberg AI, Autonomous Systems and Software Program. The undergraduate and postgraduate curriculums are about to be revised, and the research and results from the LCCC will, of course, be incorporated into them.

# The LCCC Organization

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## Governing Board

- ▶ Professor Anders Rantzer, Chair
- ▶ Professor Maria Kihl, Vice Chair
- ▶ Professor Bo Bernhardsson
- ▶ Associate Professor Giacomo Como
- ▶ Professor Charlotta Johnsson

## International Advisory Board

- ▶ Professor John Baras, University of Maryland, USA
- ▶ Professor Maria Domenica di Benedetto, University of L'Aquila, Italy
- ▶ Professor Tor Arne Johansen, Norwegian University of Science and Technology, Norway
- ▶ Professor Fadil Santosa, University of Minnesota, USA
- ▶ Professor Françoise Lamnabhi-Lagarrigue, the Laboratory of Signals and Systems, France

## Former International Advisory Board Members

- ▶ Professor Tarek Abdelzaher, University of Illinois at Urbana-Champaign, USA
- ▶ Professor Keith Glover, University of Cambridge, UK
- ▶ Professor Graham Goodwin, University of Newcastle, Australia
- ▶ Dr. Clas Jacobson, United Technologies Research Center, USA
- ▶ Professor Richard Murray, California Institute of Technology, USA
- ▶ Professor Jakob Stoustrup, Aalborg University, Denmark

## Administrative coordinator

- ▶ Eva Westin

” *None of the activities performed at the LCCC would have been possible without a well organized team of support staff working behind the scenes. Many guests have been impressed by their efficiency and service over the years and have sent us special comments on this.*

**Anders Rantzer**

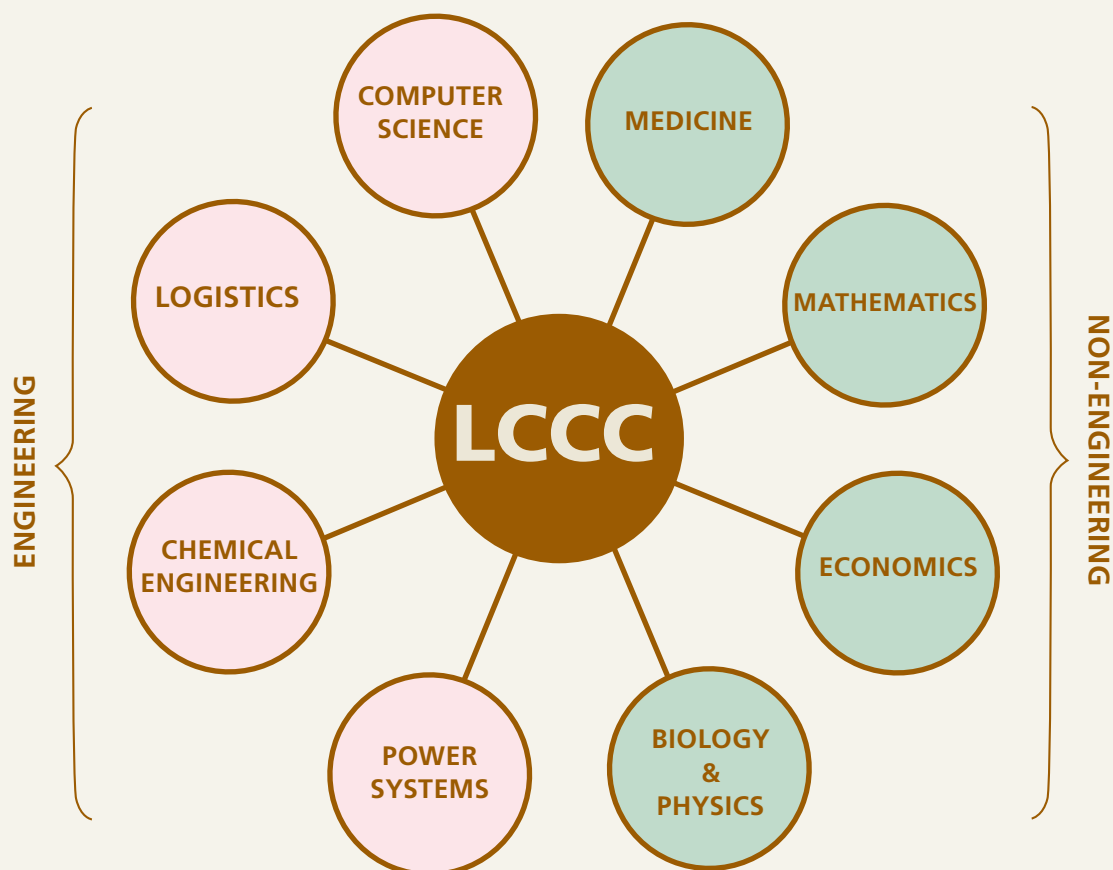
Professor at the Department of Automatic Control at Lund University, Sweden

# Collaborations within Lund University

The LCCC is a joint initiative between the Department of Automatic Control and the Department of Electrical and Information Technology at Lund University. Apart from close collaboration between researchers from these two departments, a number of other collaborations within Lund University have been initiated, creating synergies between control expertise in the LCCC and subject-specific expertise of the collaborators. Six of the eight collaborations started within the LCCC framework now have funding from other sources.

**One of the most important** collaborations has been the one within the strategic research area ELLIIT (Excellence center at Linköping-Lund In Information Technology). ELLIIT is funded by the Swedish Government as part of its initiative to promote strong research in information technology and mobile communications. It constitutes a platform for both fundamental and applied research, and for cross-fertilization between disciplines and between academic researchers and industrial experts.

**In the future,** several collaboration projects will be a natural continuation of those within the LCCC, among them the WASP (Wallenberg AI, Autonomous Systems and Software Program). This program addresses research on autonomous systems acting in collaboration with humans, adapting to their environment through sensors, information and knowledge, and forming intelligent systems-of-systems. Software is the main enabler in autonomous systems, and is an integrated research theme of the program.



# Linnaeus Environments

Through the Linnaeus grants (2006-2018), the Swedish Research Council has provided support for 40 different research environments in all scientific fields. The aim was to increase the competitiveness of Swedish research in an international context, and enable strategic choices and academic profiling for universities and higher research institutions.

Each research environment received between 5 and 10 million SEK annually for a maximum of ten years. The environments were nominated by the universities themselves, as being strong fields prioritized in each university's research strategy, and evaluated by international experts.

With 14 Linnaeus environments, Lund University has, by far, the most Linnaeus environments in Sweden. These environments have shared a total of 900 million SEK. The 14 Linnaeus environments at Lund University are listed below. 2018 was the final year of support.

” *Continuous SWOT analyses and the sharing of experiences and strategies helped to strengthen and develop the Linnaeus environments. Among many other things, the LCCC particularly emphasized the importance of having an International Advisory Board with experienced researchers at the highest level. The LCCC was also very successful in attracting top-class international postdocs and researchers.*

**Sven Strömqvist**

Professor and Pro Vice-Chancellor of  
Research at Lund University, 2008-2015

## 1 BAGADILICO

## 2 CENTER FOR ANIMAL MOVEMENT RESEARCH

## 3 CENTER FOR ECONOMIC DEMOGRAPHY

## 4 DISSECTION OF THE GENETIC AND METABOLIC COMPLEXITY OF DIABETES AND ITS COMPLICATIONS

## 5 LUND CENTRE FOR STUDIES OF CARBON CYCLE AND CLIMATE INTERACTION

## 6 LUND UNIVERSITY CENTRE OF EXCELLENCE FOR INTEGRATION OF SOCIAL AND NATURAL DIMENSIONS OF SUSTAINABILITY

## 7 EXPLORING AND CONTROLLING THE STATES OF MATTER WITH LIGHT – MULTIDISCIPLINARY LASER SPECTROSCOPY

## 8 HEMATO-LINNAEUS: A JOINT INITIATIVE TO UNDERSTAND HEALTHY AND MORBID BLOOD GENERATIONS

## 9 LUND UNIVERSITY CENTRE FOR INNOVATION AND ENTREPRENEURSHIP

## 10 NANOSCIENCE AND QUANTUM ENGINEERING

## 11 ORGANIZING MOLECULAR MATTER

## 12 THE NEURONANO RESEARCH CENTER

## 13 THINKING IN TIME: COGNITION, COMMUNICATION AND LEARNING

## 14 LUND CENTER FOR CONTROL OF COMPLEX ENGINEERING SYSTEMS

# Lund Center for Control of Complex Engineering Systems 2008-2018

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This brochure presents a popular scientific summary of the achievements of the LCCC as a Linnaeus Research Environment during the 10-year period from 2008 to 2018.

## CONTACT INFORMATION

The LCCC web site contains more information on projects, staff members and activities:

[www.lccc.lth.se](http://www.lccc.lth.se)

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