Simulation Foundations, Methods and Applications

Khalid Al-Begain
Andrzej Bargiela *Editors*

Seminal Contributions to Modelling and Simulation

30 Years of the European Council of Modelling and Simulation

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Preface

It is a great privilege for anyone to be part of any event with historic significance. This year the European Conference on Modelling and Simulation reaches the 30th milestone and I have the honour of being the President of the European Council for Modelling and Simulation as the scientific organization behind the conference. To mark this significant occasion, Springer Verlag is publishing this memorial book of selected high-impact articles from the keynotes and best papers of the last 5 years.

Modelling and simulation have become an integral part of every design process from the planning stages all through to the evaluation and validation of implementation and even beyond. Simulation has been the methodology used to designing vehicles for space explorations, in testing ideas for industrial processes and products and to understand human and living objects behaviour. It is not far from truth to state that every researcher in science, engineering, economics or medical science must have some involvement with modelling and/or simulation at various levels.

Simulation in Europe has long history and traditions and the modelling and simulation community has played significant role in the advancement of the modelling and simulation science and methodologies and effective application of the methodologies in numerous fields. The Modelling and Simulation community in Europe and as part of the international research community expressed its presence in various forums and conferences. One of the most important forums is the European Conference on Modelling and Simulation (ECMS) which is the international conference dedicated to help define the state of the art in the field. For the last 27 years, ECMS has proven to be an outstanding forum for researchers and practitioners from different fields involved in creating, defining and building innovative simulation systems, simulation and modelling tools and techniques, and novel applications for modelling and simulation. In the first chapter of this book, Professor Eugene Kerckhoffs, the first president of the European Council for Modelling and Simulation (known then as the Society of Computer Simulation—Europe) gives an account on the history of the council and the conference.

Over the last 29 episodes of the ECMS, generations of great scientists presented their work on modelling and simulation. Some were contributing to the advancement of the discipline itself, while other presenting significant contribution to other sciences and disciplines using simulation. In particular, the conference series witness countless significant keynote talks presenting significant and cutting-edge results in many areas that would require a multi-volume book to report on.

In this book, the editors opted to highlight a significant and exciting area in the application of modelling and simulation, namely the modelling of human brain. This is a common theme among the first three contributions in the book in Chaps. 2–4.

In the seminal talk in ECMS2014, Professor May-Britt Moser from the Norwegian University of Science and Technology and Nobel Prize Winner in 2014 in Physiology or Medicine, presented the results of her research on how the brain controls spatial navigation in mammals by activating functionally specialized cell types in the medial temporal lobe. A brief account of the content of the talk is given in Chap. 2.

Related to the topic, Professor Steve Grossberg reported on further research on medial entorhinal grid cells and hippocampal place cells are crucial elements in brain systems for spatial navigation and episodic memory. In his extended Abstract in Chap. 3, he summarizes the development of the GridPlaceMap neural model that explains many data about these cells and behaviours in a unified way. He also gives a thorough reference list to summarize and simulate these data. The chapter provides a high-level overview of the results, along with the unifying neural design principles and mechanisms that enable them to be realized.

Further account of significant advancement in the field is reported in Chap. 4 with the article by Professors Peter D. Neilson and Megan D. Neilson entitled "Modelling the Modeller". The authors explain that the Adaptive Model Theory is a computational theory of the brain processes that control purposive coordinated human movement. It sets out a feedforward–feedback optimal control system that employs both forward and inverse adaptive models of (i) muscles and their reflex systems, (ii) biomechanical loads on muscles and (iii) the external world with which the body interacts. From a computational perspective, formation of these adaptive models presents a major challenge.

Moving out of the human body but still in relation with human behaviour, Professor Alexander H. Levis from George Mason University, USA presents in Chap. 5 a detailed account of his work on the modelling of a human organization for the analysis of its behaviour in response to external stimuli is a complex problem which requires development and interoperation of a set of several models. Each model developed using different modelling languages but the same data, offers unique insights and makes specific assumptions about the organization being modelled. Prof. Levis shows that interoperation of such models can produce a more robust modelling and simulation capability to support analysis and evaluation of the organizational behaviour.

As a significant contribution to the simulation methodology, Professor Martin Ihrig, University of Pennsylvania, presents new research architecture for the simulation era in Chap. 6. This chapter proposes novel research architecture for social

scientists that want to employ simulation methods. The new framework gives an integrated view of a research process that involves simulation modelling. It highlights the importance of the theoretical foundation of a simulation model and shows how new theory-driven hypotheses can be derived that are empirically testable. The author describes the different aspects of the framework in detail and shows how it can help structure the research efforts of scholars interested in using simulations.

Further significant contribution to the modelling and simulation methodology is presented in Chap. 7 by Professor Witold Pedrycz from the University of Alberta with the title "Fuzzy Modeling and Fuzzy Collaborative Modeling: A Perspective of Granular Computing". The author elaborates on current developments in fuzzy modelling, especially fuzzy rule-based modelling, by positioning them in the general setting of Granular Computing. This gives rise to granular fuzzy modelling where the models built on a basis of fuzzy models are then conceptually augmented and made in rapport with experimental data. In the chapter, two main directions of granular fuzzy modelling dealing with distributed data and collaborative system modelling and transfer knowledge are formulated and the ensuing design strategies are outlined.

Staying with contributions to the methodology, Zuzana Kominkova Oplatkova and Roman Senkerik from Tomas Bata University in Zlin, Czech Republic present in Chap. 8 an article on control law and pseudo neural networks synthesized by the evolutionary symbolic regression technique. This research deals with the synthesis of final complex expressions by means of an evolutionary symbolic regression technique—analytic programming (AP)—for novel approach to classification and system control. In the first case, classification technique, a pseudo neural network is synthesized, i.e. relation between inputs and outputs are created. The inspiration came from classical artificial neural networks where such a relation between inputs and outputs is based on the mathematical transfer functions and optimized numerical weights. AP will synthesize a whole expression at once. The latter case, the AP, will create a chaotic controller that secures the stabilization of stable-state and high-periodic orbits—oscillations between several values of the discrete chaotic system. Both cases will produce a mathematical relation with several inputs; the latter case uses several historical values from the time series.

In January 2012, the world woke up on the news of a horrific accident in which a cruise liner called Costa Concordia hit a rock in the shores of Italy. This resulted is a significant loss of lives. As the investigations started, the Court was looking for methods to create better understanding of what caused the accident. It happened that the Italian group of researchers (Paolo Neri and Bruno Neri from University of Pisa and Paolo Gubian and Mario Piccinelli from University of Brescia) have developed a simple but reliable methodology for short-term prediction of a cruise ship behaviour during manoeuvres. The methodology is quite general and could be applied to any kind of ship, because it does not require the prior knowledge of any structural or mechanical parameter of the ship. It is based only on the results of manoeuvrability data contained in the Manoeuvring Booklet, which in turn is filled out after sea trials of the ship are performed before its delivery to the owner. The team developed this method to support the investigations around the Costa

Concordia shipwreck, which happened near the shores of Italy in January 2012. It was then validated against the data recorded in the "black box" of the ship, from which the authors have been able to extract an entire week of voyage data before the shipwreck. The aim was investigating the possibility of avoiding the impact by performing an evasive manoeuvre (as ordered by the Captain some seconds before the impact, but allegedly misunderstood by the helmsman). The preliminary validation step showed a good matching between simulated and real values (course and heading of the ship) for a time interval of a few minutes. Chapter 9 gives a full account of the work by the Research team as presented in ECMS conference.

In engineering it is usually necessary to design systems as cheap as possible whilst ensuring that certain constraints are satisfied. Computational optimization methods can help to find optimal designs automatically. However, the team of Lars Nolle (Jade University of Applied Science), Ralph Krause (Siemens AG) and Richard J. Cant (Nottingham Trent University) demonstrated in the work in Chap. 10 that an optimal design is often not robust against variations caused by the manufacturing process, which would result in unsatisfactory product quality. In order to avoid this, a meta-method is used in here, which can guide arbitrary optimization algorithms towards more robust solutions. This was demonstrated on a standard benchmark problem, the pressure vessel design problem, for which a robust design was found using the proposed method together with self-adaptive step-size search, an optimization algorithm with only one control parameter to tune. The drop-out rate of a simulated manufacturing process was reduced by 30 % whilst maintaining near minimal production costs, demonstrating the potential of the proposed method.

The last three chapters of the book comprise significant contributions to the analytical and stochastic modelling which were presented as part of the International Conference on Analytical and Stochastic Modelling and Applications that have been collocated with the ECMS conference.

In Chap. 11, Dieter Fiems, Stijn De Vuyst, and Herwig Bruneel, all from Ghent University discuss in Chap. 5 the packet loss problem which is an important and fundamental problem in queueing systems and their applications in modelling communications networks. Buffer overflow in intermediate network routers is the prime cause of packet loss in wired communication networks. Packet loss is usually quantified by the packet loss ratio, the fraction of packets that are lost in a buffer. While this measure captures part of the loss performance of the buffer, the authors show that it is insufficient to quantify the effect of loss on user-perceived quality of service for multimedia streaming applications.

Approximating various real-world observations with stochastic processes is an essential modelling step in several fields of applied sciences. In Chap. 12, Gabor Horvath and Miklos Telek from Budapest University of Technology and Economics, present fitting methods based on distance measures of marked Markov arrival processes. They focus on the family of Markov-modulated point processes, and propose some fitting methods. The core of these methods is the computation of the distance between elements of the model family. They first introduce a methodology for computing the squared distance between the density functions

of two phase-type (PH) distributions. Later, they generalize this methodology for computing the distance between the joint density functions of k-successive inter-arrival times of Markovian arrival processes (MAPs) and marked Markovian arrival processes (MMAPs).

Chapter 13 of the book presents a very interesting modelling concept called "Markovian Agent Models". A Markovian Agent Model (MAM) is an agent-based spatiotemporal analytical formalism aimed to model a collection of interacting entities guided by stochastic behaviours. An MA is characterized by a finite number of states over which a transition kernel is defined. Transitions can either be local, or induced by the state of other agents in the system. Agents operate in a space that can be either continuous or composed by a discrete number of locations. MAs may belong to different classes and each class can be parameterized depending on the location in the geographical (or abstract) space. In this chapter, Andrea Bobbio, Davide Cerotti, Marco Gribaudo, Mauro Iacono and Daniele Manini (Italy) provide a very general analytical formulation of a MAM that encompasses many kinds of forms of physical dependencies among objects and many ways in which the spatial density may change in time.

As stated at the beginning of the Preface, the field of modelling and simulation cover huge range of theoretical and application areas that cannot be covered in one book. The articles selected in this volume represent a small sample of the contributions over 29 conference and they meant to mark the 30th ECMS conference. On this occasion it is important to mention few people whose contributions (scientific or organizational) allowed the conference and the council to reach this significant milestone. The list will definitely not be comprehensive but I would like to mention Professor Eugene Kerckhoffs, first President of the Council, Professor Andrzej Bargiela, Past President, Dr. Evtim Petychev, Past President and Mrs Martina-Maria Seidel, ECMS Officer Manager and the tireless driving force behind the organization of all ECMS conference. Specifically, for the help in editing this book, I would like to thank Professor Robin Bye from Norwegian University of Science and Technology and General Chair of ECMS2014 for his help in getting several contributions.

Finally, the European Council for Modelling and Simulation is very grateful to the Simon Rees, Associate Editor, Computer Science, in Springer Verlag for the initiative to publish this book and for the help provided all through the process.

Prof. Khalid Al-Begain
President of the European Council of Modelling and Simulation

Contents

About the Editor

Khalid Al-Begain is a Professor of Mobile Computing and Networking at the University of South Wales (Previously called University of Glamorgan) since 2003. He is currently the President of Kuwait College of Science and Technology, leading the establishment of a new highly ambitious private university in Kuwait.

Al-Begain is still the Director of the Integrated Communications Research Centre (ICRC) at the University of South Wales, UK. He has been the Director of the Centre of Excellence in Mobile Applications and Services (CEMAS), a £5 million Centre partly funded by European Regional Development Fund (ERDF).

He received his M.Sc. and Ph.D. in Communications Engineering in 1986 and 1989, respectively, from Budapest University of Technology, Hungary. He also received Postgraduate Diploma in Management from University of Glamorgan in 2011 after finishing 2-year MBA course modules.

He has been working in different universities and research centres in Jordan, Hungary, Germany and the UK. He has led and is leading several projects in mobile computing, wireless networking, analytical and numerical modelling and performance evaluation.

Al-Begain is the President of the European Council for Modelling and Simulation (2006–2010 and 2014–date). He also was the President of the Federation of European Simulation Societies (EuroSim) leading the UK Presidency term of 2010–2013. He is the first person ever to take this role in both the organizations.

Al-Begain was a member of the Welsh Government Ministerial Advisory Steering Group for ICT in Schools. He is an UNESCO Expert in networking, British Computer Society Fellow and Chartered IT Professional, Senior Member of the IEEE and IEEE Communications and Computer Societies, member of the UK EPSRC College (since 2006) and the expert panel member of Belgium Research Funding Council (FWO), Life Fellow of the German Alexander von Humboldt Foundation, Wales Representative to the IEEE UK&RI Computer Chapter management committee and has been the UK representative to the COST290 Action management committee (2005–2009).

Al-Begain has been also appointed as Adjunct Professor at the Department of Computing and Engineering at Edith Cowen University, Australia, and as a member of the Governing Board of the West Australia Centre of Excellence on Microphotonic Systems since 2005.

So far, Al-Begain has been the General Chair of 25 international conferences. He has been the General Chair of the International Conference of Analytical and Stochastic Modelling Techniques and Applications (ASMTA) since 2003 and, in particular, he is the Founder and General Chair of the IEEE International Conference and Exhibition on Next Generation Mobile Applications, Services and Technologies (NGMAST).

He is the Winner of the IWA Inspire Wales Award for Science and Technology in 2013. He also received Royal Recognition for his contributions to the British scientific community in October 2006.

He has co-authored two books; the first entitled "Practical Performance Modelling" by Kluwer in 2001 and the second entitled: "IMS: Deployment and Development Perspective" by John Wiley & Sons in 2009. He also edited 18 books, and authored more than 200 papers in refereed journals and conferences and filed two patents. He is member of the editorial board of several international journals and acted as Guest Editor for four journal special issues. He is the co-inventor of MOSEL: The Modelling, Specification and Evaluation Language. He has already supervised over 20 successful Ph.D. projects. He has also delivered over 15 key-notes in major international conferences.

Since 2003, he secured over £300K of consultancy in major companies such as Lucent Technologies, Siemens, Telekom Malaysia and General Dynamics. He also acted as Expert Witness in the major mobile IPR court cases between Nokia–Interdigital and Nokia–HTC.

Al-Begain's research interests span over fundamental and technological themes. He is working on developing analytical and numerical models for evaluating the performance of wireless networks; in particular, the performance of mission critical systems over Voice-over-LTE 4G networks. This is a project which is backed by the world-leader General Dynamics test bed facility. He is also leading a project for modelling behavioural changes to discover early symptoms of Dementia using hidden Markov models. He also developed both routing protocols for emergency systems as well as generalized queueing models for evaluating the impact of "Propagated Failures" resulting from a disaster on systems.

On the technological side, among many projects, he led the project on the IMS based next generation service and applications creation environment at ICRC supported by major industries with a value exceeding £1 million. When created, this facility was one of very few in universities worldwide. A recent consultancy within this theme resulted in the development of world-first Mission Critical Emergency System over VoLTE.

Al-Begain has led the bidding process and secured £6.4 million funding for establishing the Centre of Excellence in Mobile Applications and Services (CEMAS). CEMAS mission was to help SMEs to design, develop, commercialize as well as adopt cutting-edge and innovative mobile applications and technologies.

He was also the Principal Investigator on ICE-WISH EU FP7 project (€4.9 million total, €300K for UoG) with 17 partners from 11 countries.

Al-Begain has also a number of company directorships including being the CEO of Myliveguard Limited (http://www.myliveguard.com/), a spinout company of the University of Glamorgan exploiting an innovative Video-to-Mobile-Phone home/office security system based on his invention.

Chapter 1
ECMS: Its Position in the European Simulation History

Eugene J.H. Kerckhoffs

Abstract This contribution describes some major aspects of the history of European simulation conferences, from the early 1970s of the previous century on. The emphasis is on how the current "European Council for Modelling and Simulation" (ECMS) with its yearly ECMS-conferences has originated in this framework and continued up to now.

Keywords History · European simulation conferences · European Council of Modelling and Simulation (ECMS) · ECMS-Conferences

ECMS stands for "European Council for Modelling and Simulation", but also for its yearly conference "European Conference on Modelling and Simulation". A bit confusing; which meaning is meant should be clear in the context. When we speak, however, of "30 years ECMS", on the occasion of which this book is published, we point to ECMS 2016 as conference number 30 in the series of yearly conferences. The first conference in the series has been held in 1987, albeit by another name: ESM, European Simulation Multiconference. ECMS as an organization, i.e. as a Council, was established a few years later in 1990, but again by a different name: initially Continental Europe Simulation Council, but already after one year renamed ESC, European Simulation Council, a Council of SCS (the Society for Computer Simulation). The author was happy to be the initiator and first chair of this Council. In 2004, the Council changed its name into the current one: ECMS. From then on ECMS is an independent forum of European academics and professional users, dedicated to research, development and applications of modelling and simulation.

1st President of ECMS (formerly ESC), current ECMS Historian
Eugene J.H.Kerckhoffs-Retired

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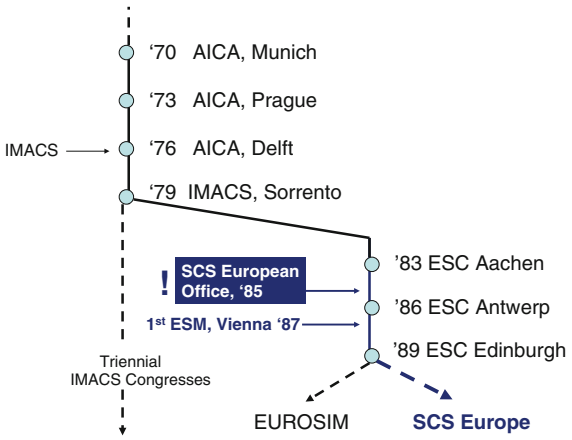

Fig. 1.1 History preceding ECMS

In the next paragraphs, we first pay attention to the simulation history before ECMS. What were the former circumstances in the European simulation community, which finally have led to the foundation of ECMS (formerly ESC)? This previous history is schematically represented in Fig. 1.1, where we start our overview in the early 1970s of the previous century.

In those days simulation was mainly continuous simulation, i.e. simulation of continuous systems; analogue and hybrid computers were used to run the simulations. For the European simulationists the major international Society was AICA, the World Association for Analogue Computing (established in 1956 in Brussels), with its triennial AICA World Congress. There existed also regional societies, such as for instance the Scandinavian Analogue Computer Society, founded in 1959 (and in 1968 renamed SIMS, Scandinavian Simulation Society). The first international congress, the author personally attended in his scientific life, was the AICA World Congress 1970 in Munich (Germany). Having been the secretary of both events, he will never forget the AICA World Congresses 1976 (Delft, the Netherlands) and 1979 (Sorrento, Italy), since both congresses have played a crucial role, which ultimately also has led to the birth of our Council ECMS (or better its precursor ESC).

During its world congress in Delft (1976), AICA was renamed IMACS (International Association for Mathematics and Computers in Simulation) to express that simulation, the covered field of interest, includes so much more than just continuous simulation and analogue/hybrid computing. From 1979 on the series of triennial IMACS World Congresses continued up to now. For especially the European simulation community the IMACS World Congress in Sorrento (1979) has been crucial. It was there that some European key simulationists get together and agreed to establish in the coming years new European "common-language based" Simulation Societies and to organize, apart from IMACS, their own triennial European Simulation Congress under the patronage of these new societies.

The first ESC (European Simulation Congress) was held in 1983 in Aachen (Germany) and organized by ASIM (the German speaking Simulation Society, founded in 1982) in close cooperation with DBSS (the Dutch speaking Simulation Society, founded in 1979). The 2nd ESC has been held in Antwerp (Belgium, 1986) and the 3rd one in Edinburgh (Scotland, 1989). During the last congress Eurosim (the Federation of European Simulation Societies) was established as an umbrella of the then consisting European Simulation Societies, such as the afore-mentioned ASIM and DBSS, the Italian Simulation Society ISCS (founded in 1985), etc.

In this European framework suddenly, in the mid-1980s, another player came on the European floor: SCS, the Society for Computer Simulation, an American Simulation Society, founded in 1954 in San Diego, with a Council in the UK (UKSC, founded in 1969). They (SCS) established in 1985 the SCS European Office at the University of Ghent in Belgium. This initiative must be seen as the very origin of the later series of ECMS Conferences!

Two years later, in 1987, the SCS European Office in Ghent organized, on behalf of the European part of SCS, an SCS European conference, actually the very first conference in our current series of 30 ECMS-Conferences! This conference has taken place in Vienna (Austria) with the name ESM (European Simulation Multiconference). Although originally the cooperation and understanding between SCS Europe and the European Simulation Societies of the Eurosim group was excellent—the 2nd European Simulation Congress ESC 1986 in Antwerp even was a common activity–, after the 3rd ESC in Edinburgh 1989 we see both organizations going their own way: the triennial European Simulation Congress ESC was continued as triennial congress, however now with the name "Eurosim Congress", and SCS Europe continued its yearly ESM (European Simulation Multiconference).

In order to provide a forum to the European SCS members outside the UK and a scientific body behind its European ESM conferences, SCS decided, by decision of the Board of Directors in its annual meeting on July 18 1990 in Calgary (Canada), to approve the submitted European proposal to establish a Continental Europe Simulation Council (CESC) as second European Council of SCS, in addition to its first European Council UKSC. All European SCS members outside the UK were automatically CESC member. The author was the initiator and chair of this new SCS Council. Already one year later CESC was reorganized to cover whole Europe including the UK, and was therefore renamed European Simulation Council (ESC); all European members of SCS were from then on ESC members. UKSC was cancelled as a separate SCS Council and became, renamed UKSim, an independent Simulation Society and as such a member society of Eurosim.

As said above, from 1989 on SCS Europe continued, independent from other European Simulation Societies, its yearly European Simulation Multiconference (ESM). In Fig. 1.2 the conferences of the first 25 years in this series are shown, from the first one in Vienna (1987) till the 25th jubilee conference in Krakow (2011). One may notice that the name of the conference has changed somewhere on the run. From 2005 on we do not speak anymore of ESM (European Simulation Multiconference) but of ECMS (European Conference on Modelling and Simulation). By this name the conference is currently known. The reason of the

change of name is a crucial change in the organization behind the conference. Until 2004 the SCS European Simulation Council and the SCS Europe Ltd (founded in 1995 to replace the SCS European Office) were, respectively, the organizational and financial body behind the conference. In 2004 however, during the 18th conference in Magdeburg, it was decided to cancel this dual system of responsibility and to continue with one organization ECMS (European Council for Modelling and Simulation), taking full responsibility for all organizational, scientific and financial issues with respect to its yearly conference; the conference was then renamed ECMS, European Conference on Modelling and Simulation.

The biggest conferences in the list of Fig. 1.2 were ESM 1990 (Nuremberg), ESM 1991 (Copenhagen) and ECMS 2007 (Prague), with each more than 200 attendants. The conferences were all in different locations, with one exception: Prague, where the conference has been held three times! All conferences were held somewhere in Europe, with again one exception: ECMS 2010 has been held in Kuala Lumpur (Malaysia), organized however by a European University (the University of Nottingham, Malaysia Campus).

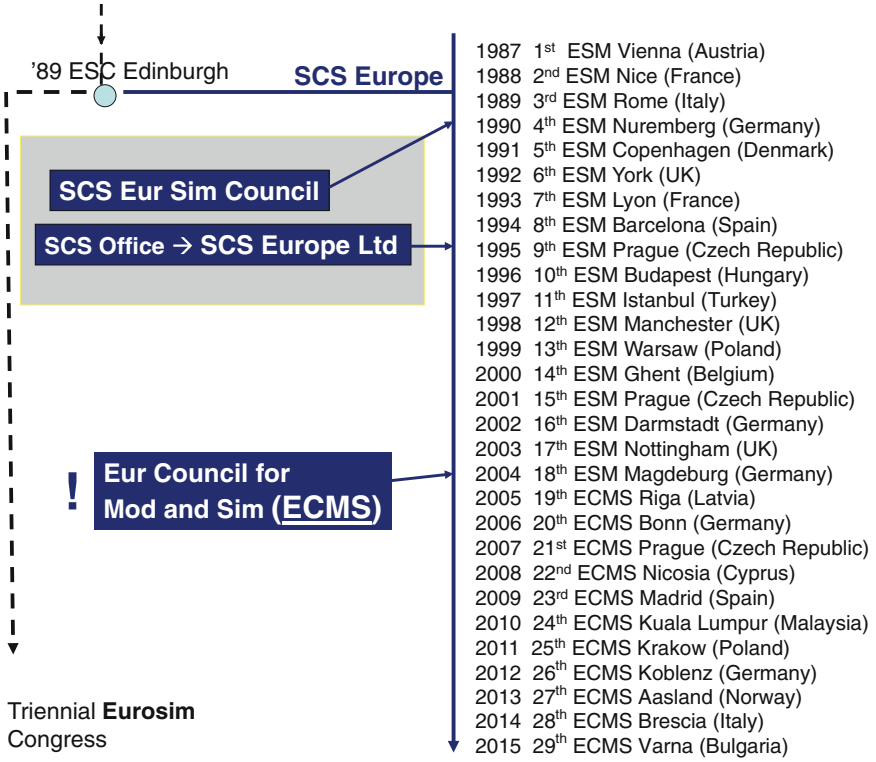

Fig. 1.2 The first 29 conferences of the ECMS series

The ECMS-Conferences of the last 5 years were: ECMS 2012 in Koblenz (Germany), ECMS 2013 in Aalesund (Norway), ECMS 2014 in Brescia (Italy), ECMS 2015 in Albena (near Varna, Bulgaria), and finally number 30 in the series: ECMS 2016 in Regensburg (Germany). All these conferences have been held in university locations, except for ECMS 2015 which has taken place in a well-equipped 5-stars hotel. The ECMS 2013 in Aalesund was special because of its very good organization and facilities; one of the keynote speakers there, prof. May-Britt Moser, got one year later in 2014 the Nobel Prize for Medicine.

ECMS is managed by a Board, chaired by the ECMS president. The presidents of ECMS (formerly ESC) were in chronological sequence: Eugene Kerckhoffs (the Netherlands, 1990–1997), Alexander Verbraeck (the Netherlands, 1997–2002), Andrzej Bargiela (UK, 2002–2006; during his presidency ESC changed into ECMS), Khalid Al-Begain (UK, 2006–2010), Andrzej Bargiela (2010–2012), Evtim Peytchev (UK, 2012–2014), and finally the current President Khalid Al-Begain (from 2014 on). Of course, the organization of the yearly ECMS Conference is not possible without the help of a "Council Office" to manage the reviewing process of the submitted papers, to manage the editing of the Proceedings, and last but not least to be the host during the conference and take care of the correct registration of the attendants. ECMS is lucky to have found in Martina-Maria Seidel a person to run the Office in an excellent manner. She started as assistant manager of the Office in 2002 (the 16th Conference, held in Darmstadt, Germany) and became a few years later the Office manager. She thus has taken care of 15 of the 30 conferences in the series; that is "1-in-2"!

The author would like to take this opportunity to congratulate ECMS with reaching this milestone of 30 conferences, and to thank all the volunteers and conference participants in these 30 years for their highly appreciated work and interest.

Chapter 2
Brain Maps for Space

May-Britt Moser

Abstract The brain controls spatial navigation in mammals by activating functionally specialized cell types in the medial temporal lobe. Key components of the spatial mapping system are place cells and grid cells. It has been known for some time that place cells are located in the hippocampus and are active only when the animal is entering a specific location in the environment. Here, we present our research results relating to grid cells. We found that grid cells are located upstream of the hippocampus, in the medial entorhinal cortex, and are activated whenever an animal enters locations that are distributed in a spatially periodic pattern across the environment. Moreover, we discovered that the grid cell network is intrinsically organized as grid cells clustered in distinct and independent grid maps with distinct scales, orientations and asymmetries, as well as distinct grid patterns of temporal organization.

Keywords Place cells · Grid cells · Grid maps · Spatial navigation

2.1 Main Contribution

The brain controls spatial navigation in mammals by activating functionally specialized cell types in the medial temporal lobe. A key component of the spatial mapping system is the place cell,located in the hippocampus. These cells—discovered by O'Keefe and Dostrovsky in 1971—are active only when the animal is entering a specific location in the environment. I will describe the discovery of another component of the mammalian spatial mapping system—the grid cell—which we found upstream of the hippocampus, in the medial entorhinal cortex, in 2005. Grid cells are activated

27th European Conference on Modelling and Simulation (ECMS) Ålesund, Norway, 27th May 2013.

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whenever an animal enters locations that are distributed in a spatially periodic pattern across the environment. The repeating unit of the grid pattern much is an equilateral triangle. Grid cells are co-localized with head direction cells and border cells, which contain information about the direction in which the animal is moving and the boundaries of the environment. Despite the discovery of several elements of the mammalian spatial map, the interaction between the components is poorly understood. We addressed this question first by using optogenetics together with electrophysiological recordings of cells in the entorhinal cortex. Hippocampal neurons were infected with an adeno-associated virus carrying genes for a peptide tag that can be visualized by fluorescent antibodies as well as the light-sensitive cation channel channelrhodopsin-2 (ChR2). The virus was engineered to enable retrograde transport through axons of cells with projections into the hippocampus. Infected entorhinal cells were detected by local flashes of light. Channel rhodopsin-expressing cells responded with a short and constant latency to the light. All cell types in the entorhinal cortex were found to respond to the light, suggesting that place signals may be generated in the hippocampus by convergence of signals from all these entorhinal cell types. In addition to discussing the transformation of entorhinal to hippocampal spatial signals, I will devote a part of my talk to asking how the grid-cell network is intrinsically organized. To address this question, we used multi-channel recording from a much larger number of cells than recorded ever before in individual animals. Grid cells were found to cluster into a small number of modules with distinct grid scales, grid orientations and grid asymmetries, as well as distinct patterns of temporal organization. The different modules responded independently to changes in the geometry of the environment.

The existence of distinct and independent modules or grid maps makes entorhinal maps different from the many other sensory cortices where functions tend to be more graded and continuous.

This is in agreement with the suggestion that the grid map is a product of self-organizing network dynamics rather than specificity in the input. Because the crystal-like structure of the grid pattern is generated within the brain, not depending on specific sensory inputs, we are confronted with a unique situation in which we, by trying to understand how the grid pattern is formed, may obtain insights into how patterns are formed in the mammalian cortex.

2.2 Editors' Comments

Professor May-Britt Moser is the Founding Director of Centre for Neural Computation and co-Director of the Kavlil Institute for Systems Neuroscience. PhD in neurophysiology, University of Oslo 1995.

She is interested in the neural basis of spatial location and spatial specifically and cognition more generally. Her work, conducted with Edvard Moser as a long-term collaborator, includes the discovery of grid cells in the entorhinal cortex, as well as several additional space-representing cell types in the same circuit.