Introduction


One contribution of 15 to a Theme Issue ‘Dynamics, control and information in delay-coupled systems’.

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Author for correspondence:
Valentin Flunkert
e-mail: flunkert@itp.tu-berlin.de

Dynamics, control and information in delay-coupled systems: an overview

Valentin Flunkert1,2, Ingo Fischer1 and Eckehard Schöll2

1 IFISC (UIB-CSIC), Universitat de les Illes Balears, 07122 Palma de Mallorca, Spain
2 Institut für Theoretische Physik, Technische Universität Berlin, 10623 Berlin, Germany

The influence of delayed coupling and feedback on dynamical systems has been investigated for several decades. However, the early studies were mostly restricted to a few systems, and powerful mathematical and computational tools to treat these systems were lacking. In recent years, more and more systems are being recognized to be influenced by or to be describable via delayed coupling. Moreover, the application of delay systems to a spectrum of applications is being pursued, ranging from encrypted communication to system control. An important aspect is that now tools have become available that allow one to study delay systems experimentally, via numerical simulations and via analytic treatment in an unprecedentedly detailed and, even more importantly, coherent manner. Therefore, in recent years, dynamical systems with delays have evolved as a major topic in nonlinear sciences. Time delays arise naturally in complex dynamical systems from many different areas of physics, biology, medicine and technology, such as nonlinear optics, electronic circuits, neuroscience, social networks, communication and logistic networks. For instance, delays may occur as memory and latency effects due to finite signal propagation and processing speeds, or may be introduced through closed-loop control schemes. In this Theme Issue, we bring together a selection of leading scientists from different fields working on delay-related problems. The aim is to address fundamental developments and state-of-the-art applications. Special attention is paid to recent foci of interest like, for instance, heterogeneity and robustness of delay-coupled networks, and distributed or state-dependent delays. Fundamentally new trends such as information processing in delayed systems and delay control of quantum systems will be included.

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It is an intriguing feature of time delay that the phase space of any ordinary differential equation subjected to delay becomes infinite-dimensional. Hence, even simple delay-differential equations are able to produce extremely complex behaviour and bifurcation scenarios. Time delay has two complementary, counterintuitive and almost contradictory facets. On the one hand, delay is able to induce instabilities, bifurcations of periodic and more complicated orbits, multistability and deterministic chaotic motion. On the other hand, delay can suppress instabilities, stabilize unstable stationary or periodic states and may control complex chaotic dynamics.

These two facets of delay are particularly fascinating in complex networks with time-delayed couplings or delayed self-feedback, which occur in various scientific disciplines. There are striking analogies between synchronization of delay-coupled lasers and neuronal networks, in both of which delay effects are abundant. Moreover, time-delayed feedback has become an important tool for controlling nonlinear dynamical systems, as exemplified by new approaches towards controlling complex networks, spatio-temporal patterns and noise-induced oscillations, bifurcation scenarios of optoelectronic oscillators, or genetic regulation and information flow in cells. Complementary to these applications, this Theme Issue also presents fundamental developments in novel theoretical concepts and sophisticated numerical analysis of these systems. For instance, new insights into the mathematical properties of stochastic delay-differential equations, functional differential equations with distributed delay given by an integral kernel, and reductive perturbation approaches to slow–fast dynamical systems with delay are reviewed.

The International Conference on Delayed Complex Systems held from 4 to 8 June 2012 at the Institute for Cross-Disciplinary Physics and Complex Systems (IFISC) in Palma de Mallorca, Spain, and co-organized with the Collaborative Research Center SFB 910 Control of Self-Organizing Nonlinear Systems—Theoretical Methods and Concepts of Application, Berlin, provided a forum for such topics. We took that opportunity to assemble a list of world leading experts, which now enables us to present perspectives of the state of the art in this field. This Theme Issue covers both applications and experiments, as well as mathematical foundations. The individual contributions summarize recent research results, but also address the broader context.

The first part addresses fundamental issues of delayed systems. The contribution by Lafuerza & Toral [1] provides an analytic treatment for stochastic birth and death models with delay, which are important models, not only in systems biology. Kyrychko et al. [2] study coupled oscillators with distributed time delay—a topic that has attracted much attention recently. The authors obtain analytic results and discuss in detail the occurrence of amplitude death in the system. Weicker et al. [3] discuss slow–fast dynamics in time-delayed systems and provide an asymptotic analysis of square-wave solutions found in many delayed systems such as optoelectronic devices.

The second part of this Theme Issue is devoted to complex networks with time-delayed couplings. The article by Atay [4] derives stability conditions for synchronization in networks with discrete or distributed delay. Much progress has been made recently in the understanding of zero-lag and cluster synchronization in networks with large delay. Kinzel [5] provides in his article a comprehensive overview over these recent developments. Höfener et al. [6] study amplitude death in networks of delay-coupled delay oscillators and analyse the influence of the network topology on the dynamics.

The third part deals with time-delayed feedback control in classical and quantum systems. The article by Amann & Hooton [7] solves a long-standing problem in time-delayed feedback control. The authors discuss how the alleged odd-number theorem of time-delayed feedback control fails in a general context and provide a corrected version. The next two articles concern the interplay of symmetry and time-delayed feedback control in coupled systems. Schneider [8] considers a system of three diffusively coupled Stuart–Landau oscillators subject to time-delayed
feedback control and analyses non-invasive stabilization of dynamical patterns in the system. The article by Postlethwaite et al. [9] discusses how spatio-temporal symmetries can be used to design non-invasive feedback to control a target solution. In the last article of this part, Emary [10] develops a novel innovative method for the control of quantum transport via delayed feedback. This work is one of few studies that apply time-delayed feedback control to quantum systems.

The last part addresses three representative areas of applications, i.e. neuroscience, optoelectronics and cell biology. Kantner & Yanchuk [11] study spiking patterns in a ring of delay-coupled Hodgkin–Huxley neurons by means of bifurcation analysis, and demonstrate the importance of communication delays for the coexistence of spiking patterns. Larger [12] provides a comprehensive overview of dynamical behaviour in optoelectronic systems. The article presents experimental results and gives analytical discussions of the wealth of dynamics observed in these systems. Masoller et al. [13] provide a two-parameter study of square-wave solutions in orthogonally delay-coupled lasers and discuss whether experimentally observed square waves have a deterministic or stochastic origin. The Theme Issue concludes with an article by Tiana & Jensen [14], who study the role of delays in gene regulatory networks. The article discusses how effective delays appear in these systems and what mechanisms evolution has found to compensate and use the effect of delays.

Owing to the cross-disciplinary nature of the topic, we hope that this Theme Issue has substantial impact across field boundaries. In particular, we hope to stimulate future developments and interactions in the areas of dynamical network science, control theory, functional differential equations, systems biology, neuroscience, nonlinear optics, information theory and quantum control theory. This Theme Issue thus provides a snapshot of the vibrant research related to delayed systems from across different fields. It will not only be of great interest to specialists working on related problems, but also provide a valuable resource for other scientists and newcomers to the field.

References


