Complex Systems Modeling Laboratory

Ihor Lubashevsky
Professor

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Research activity

As previously, in FY 2014 the research conduced by the Modeling Complex Systems Laboratory as a whole can be categorized as “Complex System Science,” which is a novel interdisciplinary branch of science studding emergent phenomena met in a wide variety of systems different in nature, spanning from traditional objects of the inanimate world and technical systems up to social, economic, and ecological systems, where human or living beings play a crucial role.

The main research interest of Prof. I. Lubashevsky concerns the basic principles and mathematical formalism required for describing social systems and human behavior, including human memory dynamics, decision-making processes, perception and recognition, prediction, and learning.

In FY2014 the research conducted by Prof. I. Lubashevsky was mainly focused on:

- analysis of the basic properties of human intermittent control over unstable systems based on mathematical modeling and hybrid human-computer experiments (in cooperation with Prof. S. Kanemoto);
- mathematical formalism required for modeling human decision-making near the perception threshold that is able to account for the bounded capacity of human cognition;

- effects of human intrinsic motivations on the decision-making and a mathematical formalism required for their modeling;
- mathematical formalism required for modeling effects of scale-free human memory.

Among the results obtained during the reported period the following are worthy of noting.

1. An original concept of the noise-induced activation governing phase transitions from the passive to active phases in human intermittent control has bee developed and verified based our experiments conducted in FY2013. Then a detailed "microscopic" model for noise-induced activation has been elaborated. It represents control activation as random walks in an energy potential, which changes in response to the state of the controlled system. The obtained results demonstrate that the double-well potential model provides tractable mathematical description of the human control properties found in the conducted experiments.
2. We have analyzed the experiments on balancing a partially visible inverted pendulum conducted in FY2013 to measure human reaction time. As the main results of this analysis, first, we have found evidence for the fact that the human reaction time is a widely distributed random variable. Second, it has been demonstrated that the reaction time distribution is of complex form and depends on the conditions of the pendulum balancing.
3. New series of experiments on the inverted pendulum balancing have been conducted; the original feature of these experiments is the possibility of tracking directly the position of mouse pointer—the visualized control actions of subjects. First, it has been directly demonstrated that in this case the control mechanism is of another nature than one found in experiments without this visualization. Second, the universality of regularities governing human control also under such conditions has been justified. Third. it has been shown that the concept of noise-induced activation holds in this case too (in collaboration with Prof. Kanemoto).
4. Based on experiments on the car-following we have demonstrated that the previously developed concept of noise-induced activation describes adequately the probabilistic properties of car driving. Then an original model of the car-following appealing to the four-dimensional extended phase space has been developed.

5. Experiments on categorical perception of gray shades have enabled us to pose a hypothesis about the existence of a certain emergent mechanism governing human decision-making under uncertainty caused by limited capacity of human cognition.

6. An original model of random walks with internal causality has been developed. These random walks are characterized by a non-symmetric diffusion tensor being constant in space. These results allow us to pose a question about *incompleteness* of the classical theories of stochastic processes.

The research interests of Prof. I. Khmyrova in FY2014 was focused on developing analytical and numerical models and simulation strategy for the light extraction through planar semiconductor-air interface of the light-emitting diode (LED). A test simulation of the LED output characteristics was performed and items which need further investigation were determined.

The research interests of Prof. M. Ryzhii are in the following areas.

- Theory and computer modeling of graphene based optoelectronic devices.
- Computer modeling of cardiac electrical activity.

External research grants received or being continued during the reported period

- "Extended Phase Space and Emergent Phenomena in Social Systems"

  JSPS "Grants-in-Aid for Scientific Research Program", Grant 2454041-00001, Duration: FY2012-FY2014 (in cooperation with Prof. Y. Watanabe)

Conducted Workshops

- A local workshop devoted to a novel concept of lens-free microscopes using dynamically formed interference patters was conducted in collaboration with Prof. Sergey Kalenkov (Moscow State University of Mechanical Engineering).

Education activity

In FY2014:

1. Under the supervision of Prof. Lubashevsky two undergraduate students defended their theses. One of them joined the Modeling Complex Systems Laboratory as master student (in partial cooperation with Prof. A. Vazhenin).

2. Under the supervision of Prof. Lubashevsky one doctoral student (A. Zgonnikov) defended his thesis.
3. Under the cooperative supervision of Profs. S. Kanemoto and I. Lubashevsky one master undergraduate student defended his thesis.

Member of laboratory taught the following courses:

Undergraduate courses:

- F3 Discrete Systems;
- P4 C++ Programing;
- NS7 Introduction to Optoelectronics;
- S2 Electric Circuits
- O3-015 Computer Simulators and Virtual Experiments on Human Cognition Near Its Threshold

Graduate courses:

- CSA17 Computer Simulation of Stochastic Processes;
- SYA04 Optoelectronics. Computer and Communication Devices;
- SYA07 Modeling of Advanced Devices;
- SYA06 Advanced Devices for Computer and Communication Systems.

Refereed Journal Papers

[i-lubash-01:2014] A. Zgonnikov and I. Lubashevsky. Double-well dynamics of noise-driven control activation in human intermittent control: the case of stick balancing. *Cognitive Processing*, DOI: 10.1007/s10339-015-0653-5:1–8, 2015.

Currently online: When facing a task of balancing a dynamic system near an unstable equilibrium, humans often adopt intermittent control strategy: instead of continuously controlling the system, they repeatedly switch the control on and off. Paradigmatic example of such a task is stick balancing. Despite the simplicity of the task itself, the complexity of human intermittent control dynamics in stick balancing still puzzles researchers in motor control. Here we attempt to model one of the key mechanisms of human intermittent control, control activation, using as an example the task of overdamped stick balancing. In so doing, we focus on the concept of noise-driven activation, a more general alternative to the conventional threshold-driven activation. We describe control activation as a random walk in an energy potential, which changes in response to the state of the controlled system. By way of numerical simulations, we show that the developed model captures the core properties of human control activation observed previously in the experiments on overdamped stick balancing. Our results demonstrate that the double-well potential model provides tractable mathematical description of human control activation at least in the considered task, and suggest that the adopted approach can potentially aid in understanding human intermittent control in more complex processes.

[i-lubash-02:2014] A. Zgonnikov, I. Lubashevsky, S. Kanemoto, T. Miyazawa, and T. Suzuki. To react or not to react? Intrinsic stochasticity of human control in virtual stick balancing. *J. R. Soc. Interface*, 11:20140636(1–13), 2014.

Understanding how humans control unstable systems is central to many research problems, with applications ranging from quiet standing to aircraft landing. Much evidence appears in favor of event-driven control hypothesis: human operators are passive by default and only start actively controlling the system when the discrepancy between the current and desired system states becomes in some sense large. The present paper argues that the control triggering mechanism in humans is intrinsically stochastic. We propose a model which captures the stochastic threshold mechanism and show that it matches the experimental data on human balancing of virtual over-damped stick. Our results suggest that the stochasticity of the threshold mechanism is a fundamental property and may play an important role in the dynamics of human-controlled systems.

[m-ryzhii-01:2014] V. Ryzhii, A. Satou, T. Otsuji, M. Ryzhii, V. Mitin, and M.S. Shur. Graphene vertical hot-electron terahertz detectors. *Journal of Applied Physics*, 116(11):114504 1–8, 2014.

We propose and analyze the concept of the vertical hot-electron terahertz (THz) graphene-layer detectors (GLDs) based on the double-GL and multiple-GL structures with the barrier layers made of materials with a moderate conduction band off-set (such as tungsten disulfide and related materials).

[m-ryzhii-02:2014] V. Ryzhii, T. Otsuji, V.Ya Aleshkin, A.A. Dubinov, M. Ryzhii, V. Mitin, and M.S. Shur. Voltage-tunable terahertz and infrared photodetectors based on double-graphene-layer structures. *Applied Physics Letters*, 104(16):163505 1–4, 2014.

We propose and theoretically substantiate the concept of terahertz and infrared photodetectors using the resonant radiative transitions between graphene layers in double-graphene-layer structures.

[m-ryzhii-03:2014] E. Ryzhii and M. Ryzhii. A heterogeneous coupled oscillator model for simulation of ECG signals. *Computer Methods and Programs in Biomedicine*, 117(1):40–49, 2014.

We present a novel model of cardiac conduction system including main pacemakers and heart muscles. Sinoatrial node, atrioventricular node and His-Purkinje system are represented by modified van der Pol-type oscillators connected with time-delay velocity coupling. For description of atrial and ventricular muscles, where depolarization and repolarization processes are considered as separate waves, we use modified FitzHugh-Nagumo model. A heterogeneous coupled oscillator model for simulation of ECG signals.

Refereed Proceeding Papers

[i-lubash-03:2014] A. Zgonnikov, I. Lubashevsky, and S. Kanemoto. To react or not to react? A double-well potential model of event-driven human control. In P. Bello, M. Guarini, M. McShane, and B. Scassellati, editors, *Proceedings of the 36th Annual Conference of the Cognitive Science Society*, pages 3155–3160, Austin, TX, 2014. Cognitive Science Society.

Understanding how humans control unstable systems is central to many research problems, with applications ranging from quiet standing to aircraft landing. Increasingly much evidence appears in favor of event-driven control hypothesis: human op- erators are passive by default and only start actively controlling the system when the discrepancy between the current and desired system states becomes large. The present study proposes a cognitive model describing the transitions between the pas- sive and the active phase of control behavior. The model is based on the concept of random walk in double-well potential widely employed in physics. Unlike the conventionally used model of fixed threshold, the proposed model is intrinsically stochastic and thus conforms to the physiological interpretation of the threshold as a probabilistic rather than deterministic notion. The model is studied numerically and is confronted to the experimental data on virtual stick balancing. The results confirm the validity of the model and suggest that the double- well potential can be used in modeling human control behavior in a diverse range of applications.

[i-lubash-04:2014] T. Suzuki, T. Miyazawa, S. Kanemoto, and I. Lubashevsky. Statistical Properties of Human Response Delay: Analysis of Virtual Stick Balancing Experiments. In *Proceedings of the 46th ISCIE International Symposium on Stochastic Systems Theory and Its Applications*, pages 236–241, Kyoto, Japan, 2014. Institute of Systems, Control and Information Engineers (ISCIE).

The present work reports the results of our experiments aimed at estimating the distribution of the response delay time in human intermittent control over unstable mechanical systems. A novel experimental paradigm: balancing an overdamped inverted pendulum was used; the overdamping eliminates the effects of inertia and, therefore, reduces the dimensionality of the system. The created simulator of balancing a virtual pendulum by a human operator via computer mouse movement makes the pendulum (stick) invisible when the angle between it and the upward position is less than 5^o. It enabled us to measure directly the delay time as the time lag between the moment when the pendulum becomes visible and the moment when a subject starts to move the mouse. involved in the experiments. The collected experimental data are presented in the form of the delay time histograms. For the analyzed system it is demonstrated, in particular, that (i) the response delay time may be treated as a random variable distributed within a wide interval. Its lower boundary is estimated as less than 50 ms, which corresponds to the limit delay time determined by human physiology. The upper boundary is estimated as 500–600 ms, which is about typical values of the response delay time when a controlled system exhibits complex dynamics. Besides, the obtained results enable us to hypothesize that the response delay in human intermittent control may be determined by cumulative actions of two distinct mechanisms, automatic and international, endowing it with complex nonlinear properties.

[i-lubash-05:2014] K. Hijikata, I. Lubashevsky, and A. Vazhenin. Markovian Random Walks on Square Lattice with Constant Non-Symmetric Diffusion Coefficients. In *Proceedings of the 46th ISCIE International Symposium on Stochastic Systems Theory and Its Applications*, pages 213–218, Kyoto, Japan, 2014. Institute of Systems, Control and Information Engineers (ISCIE).

Within the rigor typical for physical models a new type non-symmetric diffusion problem is considered and the corresponding Brownian motion implementing such diffusion processes is constructed. As a particular example, *random walks with internal causality* on a square lattice are studied in detail. By construction, one elementary step of a random walker on the lattice may consist of its two succeeding jumps to the nearest neighboring nodes along the x- and then y-axis or the y- and then x-axis ordered, e.g., clock-wise. essential that the second fragment of elementary step is caused by the first one, meaning that the second fragment can arise only if the first one has been implemented, but not vice versa. the second fragment is blocked, the first one may be not affected, whereas if the first fragment is blocked, the second one cannot be implemented in any case. elementary step these random walks are characterized by a diffusion matrix with non-zero anti-symmetric component, which is also justified by numerical simulation.

[i-lubash-06:2014] H. Ando, I. Lubashevsky, A. Zgonnikov, and Y. Saito. Statistical Properties of Car Following: Theory and Driving Simulator Experiments. In *Proceedings of the 46th ISCIE International Symposium on Stochastic Systems Theory and Its Applications*, pages 149–155, Kyoto, Japan, 2014. Institute of Systems, Control and Information Engineers (ISCIE).

A fair simple car driving simulator was created based on the open source engine TORCS and used in car-following experiments aimed at studying the basic features of human behavior in car driving. Four subjects with different skill in driving real cars participated in these experiments. The subjects were instructed to drive a car without overtaking and losing sight of a lead car driven by computer at a fixed speed. Based on the collected data the distributions of the headway distance, the car velocity, acceleration, and jerk are constructed and compared with the available experimental data for the real traffic flow. A new model for the car-following is proposed to capture the found properties. As the main result, we draw a conclusion that human actions in car driving should be categorized as generalized intermittent control with noise-driven activation. Besides, we hypothesize that the car jerk together with the car acceleration are additional phase variables required for describing the dynamics of car motion governed by human drivers.

[i-lubash-07:2014] A. Zgonnikov, I. Lubashevsky, and S. Kanemoto. Human intermittent control: concept of noise-driven control activation. In *Proceedings of the 46th ISCIE International Symposium on Stochastic Systems Theory and Its Applications*, pages 9–12, Kyoto, Japan, 2014. Institute of Systems, Control and Information Engineers (ISCIE).

Recent progress in motor control suggests that in controlling unstable systems humans switch intermittently between the passive and active behavior instead of controlling the system in a continuous manner. Traditionally, the models of intermittent control employ the notion of threshold to mimic control switching mechanisms in humans. The notion of noise-driven control activation developed here provides a richer alternative to the conventional threshold-based models of intermittent motor control. We show that the model implementing noise-driven activation matches the experimental data on human balancing of virtual overdamped stick. Our results suggest that the stochasticity of the control activation mechanism is a fundamental property and may play an important role in the dynamics of human-controlled systems.

[m-ryzhii-04:2014] V. Mitin, V. Ryzhii, T. Otsuji, A. Satou, V.Ya. Aleshkin, A.A. Dubinov, M. Ryzhii, and M.S. Shur. Terahertz and infrared detectors based on double-graphene-layer structures. In *5th Int. Symposium on Terahertz Nanoscience*, Martinique, December 2014. SPIE, Rice Univ., SPIE.

We discuss the concept of THz and IR photodetectors that are based on the resonant (and non-resonant) transitions between GLs in double-GL structures. We demonstrate that absorption spectrum and the spectral characteristics of the photodetector responsivity exhibit sharp resonant maxima at the photon energies in a widely controlled range. The applied voltage can tune the resonant maxima. We present the models of double-GL photodetectors, demonstrate their characteristics, and evaluate their ultimate performance.

[m-ryzhii-05:2014] V. Ryzhii, I. Semenikhin, M. Ryzhii, A. Satou, D. Svintsov, V. Vyurkov, , and T. Otsuji. Hydrodynamic model for double injection of electrons and holes in graphene p-i-n structures. In *The 17th Int. Workshop on Computational Electronics (IWCE)*, pages 211–212, Paris, France, June 2014. IEEE, IEEE.

Unique properties of graphene-layer and multiple-graphene-layer structures with both chemical doping and "electrical" doping in the gated structures are considered as novel building blocks for a variety of electron, terahertz, and optoelectronic devices.

[m-ryzhii-06:2014] E. Ryzhii, M. Ryzhii, and V. Savchenko. Effect of coupling on the pacemaker synchronization in coupled oscillator ECG model. In *2014 IEEE Conference on Biomedical Engineering and Sciences (IECBES)*, pages 281–286, Miri, Malaysia, December 2014. IEEE, IEEE.

We investigate the effect of diffusive voltage and current couplings between natural pacemaker oscillators in the heterogeneous coupled oscillator model of ECG signals. We study the synchronization behavior of the oscillator system for normal and fast cardiac sinus rhythms and reproduce different mode-locked cases which correspond to known incomplete atrioventricular blocks. The obtained results may help to choose reasonable coupling configurations to study heart rhythm dynamics coupled oscillator models.

[m-ryzhii-07:2014] T. Otsuji, V. Aleshkin, A. Dubinov, M. Ryzhii, V. Mitin, M.S. Shur, and V. Ryzhii. Terahertz emission and detection in double-graphene-layer structures. In *72nd Device Research Conference*, pages 159–160, Santa Barbara, USA, June 2014. IEEE EDS, IEEE.

We demonstrate that the photon-assisted resonant radiative inter-graphene-layer transitions enable the applications of the double-graphene-layer heterostructures for THz/IR lasers and photodetectors.

[m-ryzhii-08:2014] V. Ryzhii, T. Otsuji, M. Ryzhii, V. Mitin, and M.S. Shur. Graphene terahertz electronics and optoelectronics. In *The Int. Conf. "Micro- and Nanoelectronics" (ICMNE-2014)*, pages L2–03, Zvenigorod, Russia, October 2014.

We overview the concepts of several terahertz and optoelectronic devices based on single-, double-, and multiple-graphene-layer structures.

[m-ryzhii-09:2014] T. Otsuji, V. Ryzhii, S. Boubanga Tombet, T. Watanabe, A. Satou, M. Ryzhii, A. Dubinov, V. Aleshkin, V. Popov, V. Mitin, and M.S. Shur. Graphene plasmonic heterostructures for new types of terahertz lasers. In *SPIE Optics + Photonics 2014*, pages 91990F–1–10, San Diego, USA, August 2014. SPIE, SPIE.

This paper reviews recent advances in graphene plasmonic heterostructures for new types of terahertz lasers. We theoretically discovered and experimentally manifested that the excitation of surface plasmons in population-inverted graphene by the terahertz photons results in propagating surface plasmon polaritons with a giant gain in a wide terahertz range.

[m-ryzhii-10:2014] T. Otsuji, A. Dubinov V. Aleshkin, M. Ryzhii, V. Mitin, M.S. Shur, and V. Ryzhii. Terahertz lasing and detection in double-graphene-layer structures. In *LEC: 2014 Lester Eastman Conference on High Performance Devices*, pages 103–104, NY, USA, August 2014. Cornell Univ.

This paper proposes and analyzes a new type of double graphene-layer (DGL) heterostructure devices for terahertz (THz) device applications. The DGL core-shell structure has a tunnel-barrier layer sandwiched between the outer gate stack layers. When the band offset is aligned to the THz photon energy, the DGL structure can mediate photon-assisted resonant tunneling, resulting in the resonant emission or detection of THz radiation.

[m-ryzhii-11:2014] V. Ryzhii, T. Otsuji, V. Aleshkin, A. Dubinov, M. Ryzhii, V. Mitin, and M.S. Shur. Graphene plasmonic heterostructures for lasing and detection of terahertz radiation. In *RJUS TeraTech-2014: The 3rd Russia-Japan-USA Symp. On Fundamental & Applied Problems of Terahertz Devices & Technologies*, pages 8–9, Buffalo, USA, June 2014. Univ. at Buffalo.

[m-ryzhii-12:2014] V. Mitin, V. Ryzhii, T. Otsuji, M. Ryzhii, and M. Shur. Double graphene-layer structures for adaptive devices. In *SPIE DSS: 2014 Defense + Security, Conference on Micro- and Nanotechnology Sensors, Systems, and Applications VI*, pages 90830A–1–12, Baltimore, MD, USA, May 2014. SPIE.

The models of devices based on double-graphene-layer structures as well as their characteristics are discussed.

Grants

[i-lubash-08:2014] I. Lubashevsky and Y. Watanabe. Extended phase space and emergent phenomena in social systems, 2012-2014.

Kakenhi, Grant 245404100001

[m-ryzhii-13:2014] M. Ryzhii. Co-investigator on the project supported by grant-in-aid for specially promoted research “Creation of graphene terahertz lasers”, 2011-2014.

Academic Activities

[m-ryzhii-14:2014] M. Ryzhii, Dec. 2002-.

Senior Member

[m-ryzhii-15:2014] M. Ryzhii, July 1995-.

Member

[m-ryzhii-16:2014] M. Ryzhii, 2014.

Reviewer for Chaos Journal

[m-ryzhii-17:2014] M. Ryzhii, 2014.

Reviewer for European Physics B Journal

[m-ryzhii-18:2014] M. Ryzhii, 2014.

Reviewer for JSST Journal

Ph.D and Others Theses

[i-lubash-09:2014] K. Hijikata. Markovian Random Walks on Square Lattice with Constant Non-Symmetric Diffusion Coefficients, Undergraduate School, 2015.

Supervised by Prof. I.Lubashevsky: In the rigor typical for physical models a new type of non-symmetric diffusion problem is considered and the corresponding Brownian motion implementing such diffusion processes is constructed. As a particular example, *random walks with internal causality* on a square lattice are studied in detail. By construction, one elementary step of a random walker on the lattice may consist of its two succeeding jumps to the nearest neighboring nodes along the x- and then y-axis or the y- and then x-axis ordered, e.g., clock-wise. It is essential that the second fragment of elementary step is caused by the first one, i.e., the second fragment can arise only if the first one has been implemented, but not vice versa. If for some reasons the second fragment is blocked, the first one may not be affected, whereas if the first fragment is blocked, the second one cannot be implemented in any case. As demonstrated, these random walks are characterized by a diffusion matrix with a non-zero anti-symmetric component, which is also justified by numerical simulation.

[i-lubash-10:2014] A. Zgonnikov. Complex dynamics of human-controlled systems caused by uncertainty in human cognition, Graduate School, 2014.

Supervised by Prof. I. Lubashevsky. Doctoral thesis

[i-lubash-11:2014] M. Watanabe. Asymptotics of Psychometric Function of Gray Color Categorization, Undergraduate School, 2015.

Supervised by Prof. I. Lubashevsky: The results of conducted experiments on categorical perception of different shades of gray are reported. A special color generator was created for conducting the experiments on categorizing a random sequence of colors into two classes, light-gray and dark-gray. The collected data are analyzed based on constructing (i) the asymptotics of the corresponding psychometric functions and (ii) the mean decision time in categorizing a given shade of gray depending on the shade brightness (shade number). Conclusions about plausible mechanisms governing categorical perception, at least for the analyzed system, are drawn.