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研究課題名（英文） Extended phase space and emergent phenomena in social systems

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研究成果の概要（和文）：本研究の主な目的は，人間の行動および社会系のダイナミクスにおいて人間の認知容量が有限であることにより引き起こされる基本的な性質を数学的に定式化することであった．例として，2つの特徴的な問題を詳細に調べた．1つは未知の環境における動物の食糧探索を模倣するレヴィ型ランダムウォークであり，もう1つは不連続ダイナミクス，特に人間による不連続制御，をもつ系における相転移である．この問題の理解に寄与するもっとも重要な成果として，(i) 生物の意図的な行動を記述するためには，位相空間を拡張する必要があることを示し，(ii) ダイナミカルトラップモデルの新しいクラスを精緻化したこと，をあげることができる．

研究成果の概要（英文）：Mathematical formalism required for modeling human behavior affected by the bounded capacity of cognition was the main goal. Foraging problem and phase transitions in systems with intermittent dynamics governed by human actions were studied in detail. The following is worth noting. (i) As demonstrated, to describe intentional actions of living beings an extended phase space is required and the control variable has to be treated as additional component of the system phase space. In particular, acceleration is an additional phase variables required for describing foraging processes and the phase space required to model car driving has to comprise, in addition, car acceleration and the jerk (time derivative of acceleration). (ii) A novel class of dynamical trap models allowing for noise-induced activation in human intermittent control has been elaborated and a new type of emergent phenomena unique to living beings have been found theoretically and experimentally.

研究分野： 創発事象

キーワード： 創発事象　有限認知容量　非線形力学系　異常確率過程　ダイナミカルトラップ　人間の不連続制御　非平衡相転移

１．研究開始当初の背景

During the last decades it became evident that the methods of mathematical physics can be efficiently used to model various phenomena observed in individual behavior of humans as well as their large groups integrated by common activities. Opinion formation, culture and language evolution, cooperative interaction between agents in market, dynamics of traffic and pedestrian flow, and also movement of bird flocks and fish schools are typical examples of such phenomena. Currently in modeling such systems the notions and formalism developed previously in physics are mainly employed. However, objects of the inanimate and animate worlds are so different that the necessity of constructing additional formalism that could be able to allow for such basic human features as cognition, memory, motives for actions and decision-making is obvious.

Previously dealing with specific problems in traffic flow physics, we faced up to the irreducibility of its basic regularities to the classical laws of Newtonian mechanics. Keeping in mind the obtained results, we have formulated an original concept of dynamical traps caused by the bounded capacity of human cognition. The concept of dynamical traps generalizes the notion of unstable stationary points of dynamical systems playing a crucial role in the theory of emergent phenomena. As demonstrated, dynamical traps can be responsible for a new type of emergent phenomena unique to social systems or systems governed by human actions. In parallel, we posed a hypothesis that the Lévy type transport phenomena widely met in ecological and economic systems can be described appealing to active behavior of human or leaving being based on introducing additional subjective phase variables describing, e.g., motives of human actions.

For these reasons, the project has been generally aimed at elucidating the basic elements of mathematical formalism that is able to describe intentional human actions affected by the bounded capacity of human cognition. Its specific implementation has comprised two branches joined by the general goal stated above.

２．研究の目的

(1) The development of a theory of Lévy random walks based on nonlinear Markovian model for random motion of a particle described by the extended phase space made up of its position, velocity, and maybe acceleration.

(2) The development of theory of non-equilibrium emergent phenomena in social systems and systems governed by human action affected by the human fuzzy rationality. In the analyzed situations, fuzzy rationality is responsible for uncertainty and stagnation in a system motion near an equilibrium point in its neighborhood determined by the threshold of human perception.

３．研究の方法

(1) Numerical simulation based on Runge-Kutta algorithms developed by A. Rößler in 2008-2010 for solving numerically nonlinear stochastic differential equations. The concept of stochastic self-acceleration is used as a pivot point in studding the analyzed processes.

(2) Experiments based on human-computer interaction in driving a number of virtual mechanical systems. For conducting these experiments several computer simulators should be created.

４．研究成果

(1) We have developed a theory of random search performed by a wandering particle (mimicking humans in their everyday traveling or animals in foraging) that switches alternately between the “encamped” and “exploratory” movements. The two “behavioral modes” exhibit different efficiency in detecting desired targets, one of them is to search thoroughly; the other is to move fast over a relatively large distance. Roughly speaking, living beings can either move fast or search thoroughly but not simultaneously. In some sense, it is a problem of human choice under uncertainty; it is necessary to find an optimal strategy of behavior to implement random search. The key point of this mathematical approach is constructing an effective stochastic process that generates random walks meeting the Lévy statistics; the latter is the characteristic feature of real movement trajectories of animals during foraging or daily patterns formed by humans in their everyday traveling. One of its pivot points is the introduction of a new phase variable similar to particle acceleration in order to describe the decision-making of living beings under uncertainty. In some sense, it is a certain implementation of the general idea that modeling systems with essential human

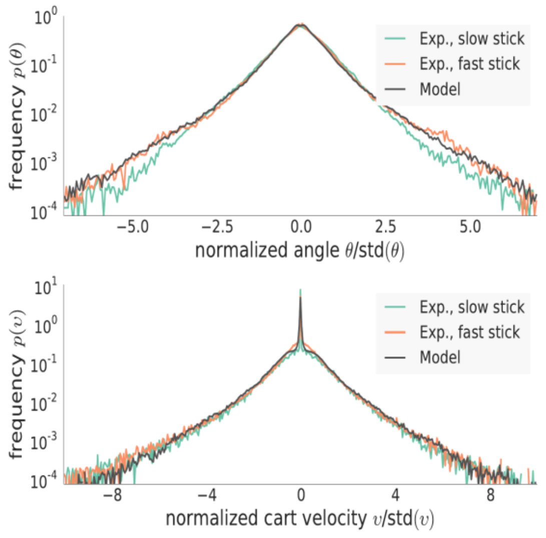
factor requires an extended phase space comprising objective and subjective components. In particular, using the time patterns and phase portraits it has been demonstrated that the developed model does generate the Lévy type random walks.

(2) The results described above (4.1) poses a question about the relationship between the constructed approach and the model called Continuous Time Random Walks (CTRW) being currently the dominant approach to describing a wide class of systems with the Lévy type transport phenomena. The most essential drawback of CTRW is that it loses the Markov property on scales of individual steps of wandering particles. The key point of the constructed approach is the result that the Lévy type behavior of the stochastic processes at hand is caused by the extreme fluctuations. To justify it a special classification of random trajectories was developed that enables one to represent the stochastic process with self-acceleration as a collection of individual spike-wise fluctuations of the governing variable; it is a certain analogy to the Itô excursions. This classification enables us to introduce the notion of the generalized CTRW by extending the initial phase space to a new phase variable describing the behavior of wandering particles. In the case of the Lévy flights it is the particle velocity, for the Lévy random walks it is the particle acceleration. Then the concept of CTRW should be applied to the corresponding stochastic process. As a possible application of the constructed theory and the subject of further investigations the following may be stated. As has become clear, there are, at least, two mechanisms of extreme events leading to various disasters. One of them is the proximity of a system to its critical state when some instability arises. This situation manifests itself in the substantial increase in the amplitude of fluctuations and their duration. So if it is the case, then monitoring the amplitude of system fluctuations one can detect the system coming to its critical state. The other is the change of the "physics" of system dynamics. For example, if nonlinear effects become essential and endow the random factors with self-acceleration, then the probability of extreme events grows drastically because now they are governed by the power-law rather than the exponential cut-off. As a result, the mean amplitude of fluctuations may vary insignificantly and their monitoring is not informative. So to detect such events it is necessary to analyze the asymptotic behavior of the system fluctuations and this information can allow one to detect critical situations.

(3) Within the framework of the fuzzy set concept the notion of dynamical traps is elaborated in details. It should be reminded that the dynamical trap is, for example, a certain neighborhood of a stationary point in the corresponding phase space wherein the motion of a system governed by a human operator is stagnated because the operator cannot recognized which point in this neighborhood is desired and all the points seem to be acceptable. However, a dynamical trap can be also a neighborhood of a certain low-dimensional multitude in the system phase space. In particular, (*i*) it has been demonstrated that the model of oscillator with dynamical trap may be regarded as the generalization of the stationary point being the key notion in the theory of dynamical systems and the theory of emergent phenomena. It was done for systems possessing the locus of partial equilibrium; car following is a characteristic example of such systems. A new approach has been proposed to describe the fuzzy human control over unstable systems in terms of dynamical traps. Based on these results it has been demonstrated that the human fuzzy rationality can play the role of a new mechanism of emergent phenomena in social systems and systems governed by human operators. Using the "lazy bead" model, it has been shown that dynamical traps can cause new type non-equilibrium phase transitions with complex properties, e.g., exhibiting on-off intermittency as well as the standard behavior of the first order phase transitions. (*ii*) A novel concept of active dynamical traps has been developed. The key point is the extension of the system phase space including a new phase variable describing the active behavior of human operators. From our current point of view, exactly this concept is the most appropriate mathematical formalism for human actions near the perception threshold. It is demonstrated that on their own active dynamical traps can cause complex behavior of such systems.

(4) Understanding how humans control unstable systems is central to many research problems, with applications ranging from quiet standing to aircraft landing.

The concept of human intermittent control is a modern paradigm in this field. It assumes the actions of a human operator to be a sequence of alternate fragments of active and passive phases of human behavior. Now the event-driven control hypothesis is widely used: 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. We have conducted a series experiments on balancing virtual over-damped pendulums and developed an original theory explaining the found experimental results. This theory argues that the control triggering mechanism in humans is intrinsically stochastic. The proposed model captures the stochastic threshold mechanism and show that it matches the experimental data on human balancing of virtual over-damped pendulum collected during the experiments note above. 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. The model employs the concept of dynamical traps with respect to the pendulum angular velocity reduced to the cart velocity and the standard dynamics of the pendulum attached to the cart moved by the operator (via PC mouse). This model uses the extended phase space allowing for human active behavior and comprising not only the angle between the pendulum and its upright position but also the cart velocity. It should be reminded that without human control the pendulum with over-damped dynamics is described by one-dimensional model whose phase space contains only the angle. It is shown that the extension of the phase space is due to the active phase of the operator behavior being governed by the open-loop control mechanisms.



The upper plot in the figure on the left illustrates the universality of the found statistical characteristics of human actions; the distribution functions of the main system variables are of the same form independently of the skill, gender, age of the participants as well as the difficulty of balancing. The subject’s individuality are reflected only in the scales.

The lower plot in this figure illustrates another important result; it is a sharp peak of the velocity distribution located at the origin. The existence of this peak means that during a macroscopic time interval the operators did not move the PC mouse, which is related directly to the passive phase of the human intermittent control. Based on this result we have drawn the conclusion that such peaks can be treated as a characteristic feature pointing to the fact that the intermittent control is pronounced in a system under consideration. So in the given case the cart velocity has to be treated as a new dynamical variable describing the operator actions.

To describe the active phase implementation as open-loop control fragments an original approach has been proposed. It uses the concept of dynamical programming dealing with the following optimization problem with respect to the strategy of the operator actions in the forthcoming future during a given fragment of the active phase.

To justify the developed phenomenological model of subject’s actions in balancing over-damped inverted pendulum, a model for the operator’s behavior has been developed. The transitions between the passive and active phases are described in terms of random variable, the order parameter, switching intermittently between the operators’ two cognitive states, “wait” and “act.” Appealing to the phase space extension approach, we consider the cart velocity an independent phase variable, so that its dynamics is determined by a separate differential equation. The order parameter is driven jointly by the deterministic and random forces. The deterministic dynamics is governed by the double-well potential energy landscape, where the configuration of the landscape is determined by the state of the controlled system. The stochastic switching between the two wells is caused by a random force. The obtained results demonstrate that the double-well potential model provides tractable mathematical description of the human control properties found in the conducted experiments.

(5) Driving a car in following a lead car is a characteristic example of human control. It allows us to hypothesize that the intermittency of human control should be pronounced in the driver behavior and affect the car motion dynamics essentially. The conducted *pilot* experiments employing the TORCS car-driving simulator have demonstrated that the behavior of subjects involved into driving virtual cars should be categorized as the generalized intermittent control over mechanical systems. It consists of a sequence of alternate fragments of active and passive phases of driver behavior. The passive phase is characterized by the fact that during the corresponding time interval a driver does not change the position of the gas or break pedals. In this case the jerk (jolt, the rate of change of acceleration) plays the role of the parameter controlled directly by the driver and, so, has to be regarded as an independent phase variable determining the car dynamics. It enabled us, keeping on mind also driving real cars, to *hypothesize* that a sophisticated description of car motion controlled by human actions requires the introduction of four dimensional phase space, where the car position, velocity, acceleration, jerk are the independent variables. A new model for the car-following that allows for these features has been proposed. Its numerical simulation has demonstrated that the combination of the concepts of the noise-driven activation in human intermittent control and the action dynamical traps caused by the bounded capacity of human cognition can reproduce, at least, qualitative the results collected in the conducted experiments.

５．主な発表論文等

（研究代表者、研究分担者及び連携研究者には下線）

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〔その他〕
ホームページ等
5 additional publication at arXiv.org

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