System Theoretic Viewpoint on Modeling of Complex Systems: Design, Synthesis, Simulation, and Control

Armen G. Bagdasaryan †
Institution of the Russian Academy of Sciences
V.A. Trapeznikov Institute for Control Sciences of RAS
Russia

Abstract: We consider the basic features of complex dynamic and control systems, including systems having hierarchical structure. Special attention is paid to the problems of design and synthesis of complex systems and control models, and to the development of simulation techniques and systems. A model of complex system is proposed and briefly analyzed.

Key–Words: Systems, Complexity, Control, Modeling, Simulation, Computer Simulation Systems

1 Introduction

The science of complex systems is a multidisciplinary field aiming at understanding the complex real world that surrounds us. Examples of these systems are neural networks in the brain that produce intelligence and consciousness, artificial intelligence systems, swarm of software agents, social insect (animal) colonies, ecological systems, traffic patterns, biological systems, social and economic systems and many other scientific areas can be considered to fall into the realm of complex systems.

Complex systems contain a large number of mutually interacting entities (components, agents, processes, etc.) whose aggregate activity is nonlinear, not derivable from the summations of the activity of individual entities, and typically exhibit hierarchical self-organization. Another important characteristic of complex systems is that they are in some sense purposive. The description of complex systems requires the notion of purpose, since the systems are generally purposive. This means that the dynamics of the system has a definable objective or function.

Each element of a complex system interacts with other elements, directly or indirectly. The actions of or changes in one element affect other elements. This makes the overall behavior of the system very hard to deduce from and/or to track in terms of the behavior of its parts. This occurs when there are many parts, and/or when there many interactions between the parts. Since the behavior of the system depends on the elements interactions,
an integrative system-theoretic (top-down) approach seems more promising, as opposed to a reductionist (bottom-up) one.

Any scientific method (approach) of studying complex real world systems relies on modeling (analytical, numerical) and computer simulation.

The study of complex systems begins from a set of models that capture aspects of the dynamics of simple or complex systems. These models should be sufficiently general to encompass a wide range of possibilities but have sufficient structure to capture interesting features.

Most of the complex systems can be studied by using nonlinear mathematical models, statistical methods and computer modeling approaches. For this both analytical tools and computer simulation are adopted. Among the analytical techniques are statistical mechanics, stochastic dynamics, non-equilibrium thermodynamics, etc. Among the computer simulation techniques are cellular automata, multi-agent techniques, evolutionary programming, Monte Carlo methods, etc. However, the analytical methods alone do not allow us to understand a complex system. Since analytical treatments do not yield complete theories of complex systems, computer simulations play a key role in our understanding of how these systems function and work. This is also true and possibly in a more degree for complex control systems. The main characteristic of modern complex control systems is that it is impossible to uniquely and adequately describe these systems, using classical mathematical methods. Classical mathematical models and approaches are yet suitable and applicable just for a few problem domains, which are static and comprehensible, and have most general properties. But in complex dynamic environments, with an increase of complexity, problem domains become dynamic, requiring for dynamic solutions that will be able to adapt to the changes in the problem domain, and there still remains a wide range of problems that can not be described by the existing formal methods.

2 Basic Peculiarities of Complex Systems

Basic reasons that make it difficult for complex (control) systems to be described by formalized methods are the following ones:

- Information incompleteness on the state and the behavior of a complex system;
- Presence of a human (observer) as an intelligent subsystem that forms requirements and makes decisions in complex systems;
- Uncertainty (inconsistency, antagonism) and multiplicity of the purposes of a complex system, which are absent in a precise formulation;
- Restrictions imposed on the purposes (controls, behavior, final results) externally and/or internally in relation to a system are often unknown;
- Weak structuredness, uniqueness, combination of individual behaviors with collective ones are the intrinsic features of complex systems.
Complex systems are different from simple systems by their capabilities of:

- **Self-organization** - the ability of a complex system to autonomously change own behavior and structure in response to events and to environmental changes that affect the behavior.

  For systems with a network structure, including hierarchical one, self-organization can amount to: (1) disconnecting certain constituent nodes from the system, (2) connecting previously disconnected nodes to the same or to other nodes, (3) acquiring new nodes, (4) discarding existing nodes, (5) acquiring new links, (6) discarding existing links, (7) removing or modifying existing links.

- **Co-evolution** - the ability of a complex system to autonomously change its behavior and structure in response to changes in the system environment and in turn to cause changes in the environment by its new (corrected) behavior.

  Complex systems co-evolve with their environments: they are affected by the environment and they affect their environment.

- **Emergence** - the property that emerge from the interaction of constituent components of a complex system.

  The emergent properties do not exist in the components and because they emerge from the unpredictable interaction of components they can not be planned or designed.

- **Adaptation** - the ability of a complex system to autonomously adjust its behavior in response to the occurrence of events that affect its operation.

  Complex systems should adapt quickly to unforeseen changes and/or unexpected events in the environment. Adaptation enables the system to modify itself and to revive in changing environment.

- **Anticipation** - the ability of a system to predict changes in the environment to cope with them, and adjust accordingly.

  Anticipation prepares the system for changes before these occur and helps the system to adapt without it being perturbed.

- **Robustness** - the ability of a system to continue its functions in the face of perturbations.

  Robustness allows the system to withstand perturbations and to keep its function and/or follow purposes, giving the system the possibility to adapt.

It is well-known that to control is in some sense to anticipate. For modeling and analysis of complex systems in the presence of principally non-formalizable problems and impossibility of strict mathematical formulation of a problem, heuristic, cognitive and robust approaches and methods can be applied.
However, if there exists a sufficiently exact and adequate formal description of a complex system (object, process) and we have a sufficient initial information, then heuristics, cognition and robustness is not required. But these are of a great need when there is a lot of uncertainty in the description of a complex system (object, process); a system has conflicting and/or inconsistent purposes; lack of initial information; problems are ill-posed.

3 Complexity, Modeling and Control

Complex systems are more often understood as dynamical systems with complex, unpredictable behavior. Multidimensional systems, nonlinear systems or systems with chaotic behavior, and also the systems, which dynamics depends on or determined by human being(s), are the formal examples of complex systems. Complex systems have specific characteristics, among them: (1) uniqueness; (2) weak structuredness of knowledge about system; (3) the composite nature of system; (4) heterogeneity of elements composing the system; (5) the ambiguity of factors affecting the system; (6) multivariation of system behavior; (7) multicriteria nature of estimations of system’s properties; and, as a rule, (8) high dimensionality of system.

Under such conditions, the key problem of complex systems theory consists in the development of methods of qualitative analysis of the dynamics of such systems and in the construction of efficient control techniques. In a general case, the purpose of control is to bring the system to a point of its phase space which corresponds to maximal or minimal value of the chosen efficiency criterion. Another one of the main and actual problems in the theory of complex systems and control sciences is a solution of "ill-posed, weakly- and poorly-structured and weakly-formalizable complex problems" associated with complex technical, organizational, social, economic, and cognitive and many other objects, and with the perspectives of their evolution. Since the analysis and efficient control are impossible without a formal model of a system, the technologies for construction (building) models of complex systems have to be used.

Complexity of a system is a property stipulated by an internal law of the system that defines some important parameters, including spatial structure and properties of the processes in this structure. This definition of complexity is understood as certain physical characteristic of nature.

Since it is nonlinearity of internal regularities (laws) that underlies complexity of real world systems, complexity and nonlinearity are sometimes considered as synonyms. The more complex a process or geometrical form of a system (object), the more it is nonlinear.

Today we can distinguish several basic forms of complexity: structural (geometrical, topological), dynamical, hierarchical, and algorithmic. However, other possible forms of complexity can be found as well. For example, one that comes from large scales. Algorithmic complexity finds itself in many software systems. These are the most complex systems developed by human being, although their structure and dynamics are comparatively simple. Structural, dynamical, algorithmic, hierarchical and large-scale complexity of systems
attracts much of attention because we face them, manifestations of nonlinearity of nature, in our everyday life.

Interplay between intellectualized mathematical and information technologies of control and decision support plays an important role in modeling of processes of evolution and functioning of complex (large-scale) systems.

Complex systems are usually difficult to model, design, and control. There are several particular methods for coping with complexity and building complex systems.

At the beginning, a conceptual model of system is developed, which reflects the most important, in the context of the problem under study, material and energy and information processes taking place between different elements of system (that is, its subsystems), internal states of which can be considered as independent. This kind of model determines the general structure of system and it should be complemented by algorithmic and, more often, by mathematical models of each of subsystems. These models can be represented by graph models, Petri nets models, system dynamics models or by their combination. The obtained models are aggregate that reflect the dynamics of the most important, for current investigation, variables. Then, the next step consists in checking the mathematical models for their behavioral adequacy to real system, and in identification of parameters of the models over the sets of admissible external actions and initial/boundary conditions. The difficulties of solution of these problems increase as the system becomes more complex. For this reason, another important step is structuring of problem domain (or situations), control domain, and simulation scenarios. For these purposes, stratified models, state (or flow) diagrams models, system dynamics models, aggregate models and robust identification can be used. However, the developed model should be subjected to intense analysis and possible changes after its testing for structural controllability, observability, identifiability, and sensitivity. These properties guarantee the model crudity in a given class of variations of the problem conditions and, as a consequence, the reliability and accuracy of system simulation. Besides, the crudity enables one to reduce the model to canonical (more simple) forms which leads to significant simplification of modeling, control synthesis, and analysis of the system.

Thus, when constructing a model of complex dynamical system, three forms of its description arise: (1) conceptual model; (2) formalized model; (3) mathematical model; and (4) computer model.

4 Analysis of Complex Systems and Their Abstract Description

In system analysis, the problem of structuring of complex systems and processes, their goals, functions, behaviors, etc., is a highly topical problem. Structure is fundamental and, possibly, the most important characteristic of system. Structure can be considered as a set of elements and relations between them, which provides integrity, stability and identity of system under various external and internal changes. One of the main problem of system analysis is building of graphic model describing the existing system of relations and
connections between elements. The general problem of analysis is to clarify and estab-
lish structural properties of system and its subsystems in a whole, starting from a given
description of system elements and relations.

At modern stage of the development of systems and control theory, it is more efficient
to analyse and model systems not at the level of the systems (control systems) themselves
but at the level of the structures of (control) systems. Many definitions of abstract system
$S$ at the set-theoretic level use ternary description. For example, the notion of abstract
system is constructed with use of the following three components: "objects - connections
(relations) - properties (attributes)” [A. Hall] or "set of elements - relations - environment”
[von Bertalanfi]; summing up various definitions, we can arrive at

$$S = \langle E, R, L \rangle,$$

where $E$ is a set of basic elements (subsystems), $R$ – a set of relations (or connections)
between elements, $L$ – a set of laws and rules that enables constructing different composi-
tions (structures, etc), using basic elements of $E$ and $R$. In some definitions, a set $L$ is
substituted by a set of structures $Struct$, which can be considered as a result of action of
operator $L$ on the sets $E$ and $R$. Therefore, depending on the chosen basic elements, one
can consider several forms of structures of complex system when studying it. This defi-
cation can be complemented by other important components, such as parameters, goals,
properties, etc. However, it still remains a simplified description of system and it does not
satisfy the modern level of knowledge and system requirements. The notion of system has
evolved from "elements and relations” to "goals and goal-setting” and then to "observer
and language”: system is a reflection, on the language of observer (researcher), of objects,
relations and their properties in the course of study and cognition.

Let us consider the definition of system, complementing (1) with the following compo-
nents

$$S = \langle E, R, Struct, P, W, G, Strat, Rs, S_E \rangle$$

where $E, R, Struct$ are as defined above, $P$ is a set of parameters of system elements, $W$ –
integrative properties of system, $G$ – goals of system functioning, $Strat$ – a set of strategies
of system evolution or development (possible directions, algorithms, mechanisms of self-
organization, adaptation), $Rs$ – a set or resources required for development, $S_E$ – a set of
states of environment influencing a system. Combinations of different components give us
some simple models that can be analyzed. For example, the combination $(Struct, E, R)$
reveals a mechanism of formation of different structures from elements of $E$ and $R$; the
combination $(Struct, P, W)$ is related with the formation of system properties on the basis
of parametrization of structure, that is by assigning the elements of structure the certain
values of parameters; the combinations $(Struct, E, G)$, $(Struct, P, G)$, $(Struct, W, G)$ all
reveal the influence of both elements of structure and the structure itself and also its pa-
rameters and system properties on the formation of goals; the combinations $(Struct, E, W)$
and $(Struct, R, W)$ activate formation of system properties as both elements of structure
and the structure itself; the combinations \((W, P, G)\), \((W, R, G)\) and \((E, W, G)\) provide a solution for the problem of consistency of system properties and its goals, using structure, parameters, relations, and elements; the combinations \((E, P, Rs, Strat)\), \((Struct, P, G, Strat)\) determine the strategies of system evolution with elements, resources and changes in values of system parameters, and also interconnect evolution of system with its goals; the combination \((Struct, R, P, S_E)\) reveals the influence of environment on the formation of structures through changes in values of system parameters, appearance of new relations or changes of existing relations in systems. In the same manner, other combinations can be constructed and analyzed.

The model (2) can be further extended by a set of plans \(Plans\), which is associated with knowledge base represented by production rules or semantic networks, and by a set of controls \(C\) influencing a system evolution and for purposeful taking of system to the desired state, the point in the phase space of system. And finally, we have the following model of complex system

\[
S = < E, R, Struct, P, W, G, Plans, Strat, C, Rs, S_E >.
\] (3)

It is obvious that analysis of complex systems includes analysis of a large number of interrelated combinations. One possible way to reduce the number upon analyzing the structures is to parametrize the structure of system, elements of system and relations between them.

5 Mathematical and Computer Simulation of Complex Systems

It is inevitable that when modeling of complex systems one has to deal with aggregate models. For these purposes, the system theoretic notion of an "aggregate" can be used.

Let \(T\) be a subset of real numbers (the set of time moments), \(X, U, Y, Z\) be sets of any nature. Elements of these sets are: \(t \in T\) is a time moment; \(x \in X\) is an input signal; \(u \in U\) is a control signal (action); \(y \in Y\) is an output signal; \(z \in Z\) is a state. States, input, control and output signals are considered as functions of time, \(z(t), x(t), u(t)\) and \(y(t)\).

An aggregate is then defined as

\[
<T, X, U, Y, Z, H, Q>
\]

where \(H\) and \(Q\) are operators (generally speaking, random operators); \(H\) is transitions operator, \(Q\) is outputs operator. These operators realize the functions \(z(t)\) and \(y(t)\). The structure of these operators distinguishes the aggregates among any other systems.

Aggregates are quite general mathematical schemes, special cases of which are boolean algebras, contact relay networks, finite automata, dynamical systems, and some other mathematical objects. Because of using of aggregate models, the necessity of development of special computer tools which are adequate to such a description arises. This can be reached by construction of the so-called aggregate simulation systems.
As it was mentioned earlier, construction of model of complex system consists of three forms of its description: conceptual, formalized, mathematical, and computer ones. Conceptual model reflects informative description of system with use of an informal language. Mathematical description serves as a basis for computer model, which is then transformed to computer simulation system with the help of specialized modeling languages. The main purpose of computer simulation system is to analyse dynamic behavior of system by describing the state changes with time, to predict and compare the consequences of alternative (control) actions or changes in values of system parameters, to evaluate various strategies of system evolution and functioning. Simulation systems provide solution of such problems as evaluation of efficiency of different control principles, comparative analysis of system structures, analysis of the influence of parameters and external conditions on system functioning.

Simulation system, which as a rule consists of a number of simulation models, should meet the following requirements to:

- **Model completeness.** The models should provide sufficient possibilities for obtaining the necessary characteristics of system with the required accuracy, reliability, and confidence;
- **Model flexibility.** The models should enable one to reproduce various situations upon changing of system parameters;
- **Model structure.** The models should provide the possibility of modification of their separate parts;
- **Information support.** It should provide the information compatibility of models with computer databases.

In the process of development of simulation models two approaches are used: discrete and continuous. Choosing of the approach is determined to much extent by the properties of system and by the character of influence of external environment on the system. For example, Monte-Carlo methods can be considered as a special case of discrete probabilistic simulation models. When using the discrete approach to the development of simulation models, abstract systems (mathematical schemes) of three basic types are normally applied: automata systems, queueing systems, and aggregate systems. In case of continuous approach the system which is modeled is formalized, independently on its nature, in the form of continuous abstract system, between elements of which the flows of one or another nature circulate. The structure of such a system is graphically represented in the form of flow diagrams (schemes).

In general case, simulation model of system can be understood as a system consisting of separate subsystems (elements, components) and connections between them; the functioning (changes of states) and internal change of all the elements of system under the action of connections can have an algorithmic realization, as well as the interaction of system with the environment. Then the simulation of system is reduced to the step-by-step reproduction
of the process of functioning of all system elements with regard to their interactions and the influence of the environment. Simulation is more efficient when used at the higher level of hierarchy, where the interaction of a large number of complex objects (processes) is considered on time scales.

Computer simulation system can be developed with the use of universal languages of higher level or with the use of specialized simulation languages. Today, a number of simulation languages and systems are developed, such that SIMULA, GPSS, GASP, SLAM, SIMSCRIPT, SIMAN, SIMNET, SIMPLE, MODELICA, SIMULINK, and others.

So, the most important components of computer (aggregate) simulation system are the following:

- *Simulation model* of complex system (process) along with the software that realizes the computer model;
- *Dialog system* that supports the formation of modeling scenarios;
- *Internal mathematical software* that provides planning and implementation of simulation (computational) experiment;
- *External mathematical software* that provides monitoring and management of the process of simulation experiment;
- *Mathematical software of decision support process* that provides the means of analysis of various control and behavior scenarios and optimal decision making;
- *Standard modules library* containing a set of software modules that implement standard operations;
- *Programming language of higher level* which is used for structural transformation of (aggregate) models, responsible for the formation of input and output information (data) flows.

To make a computer simulation system more closer to the end-user in order he/she be capable of conducting experiments independently, the system should be problem-oriented. The development of the corresponding tools of problem-oriented simulation is a vital and topical direction in the field of system modeling technology.

6 Conclusion

The basic features and properties of complex systems are considered and analyzed in the context of modeling and simulation. We also discussed in detail the problems of construction of design and control models, and issues of building complex systems as well. We proposed a set theoretic model of complex system. The proposed model is quite general and can be applied for a wide class of systems. The model has been extended in order to be applicable for the case of intelligent complex systems. Much attention has been paid to the development of computer simulation systems and to the analysis of their components.
References:

[1] M. Mesarovic, Y. Takahara, General Systems Theory: Mathematical Foundations. N.Y.: Academic Press, 1975

[2] D. Norman, M. Kuras, Engineering complex systems, in *Complex Engineered Systems: Science Meets Technology*, D. Braha, A. Minai, Y. Bar-Yam (Eds.). Springer, 2006, pp. 206-245.

[3] C. Anderson, Creation of desirable complexity: strategies for designing self-organized systems, in *Complex Engineered Systems: Science Meets Technology*, D. Braha, A. Minai, Y. Bar-Yam, Eds., Springer, 2006, pp. 101-121.

[4] K. Mainzer, *Thinking in Complexity. The Complex Dynamics of Matter, Mind, and Mankind*. Heidelberg: Springer-Verlag, 1997.

[5] Paul A. Fishwick, *Handbook of Dynamic System Modeling*, Chapman & Hall/CRC, 2007

[6] S. Lee, S. Cho, et al., A layered agent oriented engineering approach for building complex systems, in *Proceedings of the WSEAS International Conference on Systems*, Athens, Greece, 2006, pp.681-686

[7] A. Bagdasaryan, *Discrete modeling and analysis of complex dynamic systems in the control mode*, Moscow, 2005

[8] V. Latora, M. Marchiori, *The Architecture of Complex Systems*. Santa Fe Institute for Studies of Complexity, Oxford University Press, 2003

[9] M. E. J. Newman, The structure and function of complex networks, *SIAM Review* **45**, pp. 167-256, 2003

[10] A. Bagdasaryan, Mathematical and computer tools of discrete dynamic modeling and analysis of complex systems in control loop, *Int J Mathematical Models and Methods in Applied Sciences* **2**(1), 2008, pp. 82-95

[11] B. Edmonds, Complexity and scientific modeling, *Foundations of Science* 5, 2000, pp. 379-390

[12] Y. Bar-Yam, *Dynamics of Complex Systems*. Reading, MA: Addison- Wesley, 1997