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A New Kind Methodology for Controlling Complex Systems

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Abstract—Control of complex systems is one of important files in complex systems, that not only relies on the essence of complex systems which is denoted by the core concept – emergence, but also embodies the elementary concept in control theory. Aiming at giving a clear and self-contained description of emergence, the paper introduces a formal way to completely describe the formation and dynamics of emergence in complex systems. Consequently, this paper indicates the Emergence-Oriented Control methodology that contains three kinds of basic control schemes: the direct control, the system re-structuring and the system calibration. As a universal ontology, the Emergence-Oriented Control provides a powerful tool for identifying and resolving control problems in specific systems.

Keywords—Complex System Control; Emergence; Emergence-Oriented Control Methodology.

I. Introduction

Stephen Hawking has stated the 21th century will be the century of complexity. Complex systems, systems with complexity, are treated as the hottest scientific research area by many researchers. The research of complex systems is the need of the development of modern society and high technology, and a critical challenge for many areas of science and technology.

In general, a complex system, characterized with self-organization, adaptation, evolution, etc., consists of plenty of constituents which interact in a hierarchical frame to function as a whole. Emergence, self-organization, adaptation and evolution are the elementary properties of complex systems; and emergence is the essential characteristic. The aim of complex system research is to develop and present the theory and implications of the system-level structures and behaviors generated by interactions among constituent-level components.

One of the aims of complex system research is to develop and present the theory and implications of the higher-level structures and behaviors generated by interactions among lower-level components. Another goal is to find effective control methods or approaches according to predefined requirements and/or goals in specific systems. As well as the research of control of complex systems focuses on control approaches and methods that can change structures and behaviors of controlled systems under goal-constrains, by integrating the elementary characteristics of complex systems and the basic approaches of system control.

Emergence, as the identifying feature, embodies the instinct of complex systems. It is treated as the core characteristic, as well as can be explain as it is system-level phenomenon generated from constituent-level components and interactions among them. Therefore, understanding emergence is the first task when studying the theory of complex systems.

In this paper, we denote a formal explanation to try to provide a deep understanding of emergence, on which a control methodology called Emergence-Oriented Control (EOC) is indicated. According to the principals and the elementary characteristics of complex system control, three control schemes in EOC are defined to provide ontology for controlling complex systems. It is important to the research on theories and applications that make clear the general characteristics, processes and methodology of complex system control, not only because the explicit understanding of the characteristics can help people on further research; but also because the universal descriptions of the processes and the methodology can provide the basis for establishing control methods in specific applications.

II. Complex System Control

A. Complex Systems

The study of complex systems in a unified framework has become recognized in recent years as a new scientific discipline, the ultimate of interdisciplinary fields[1]. Complex systems, known as the science of 21st century, are defined and described by researchers from various disciplines, which causes lack of a generally accepted definition for complex systems. The research of complex systems tries to reveal and understand the deep commonalities among artificial systems, human societies and natural systems. For the sake of the commonalities, theories of complex systems cross disciplines.

1) Definitions: When it comes to complex systems, a freely accepted formal definition lacks, as well as there are plenty of descriptions in natural languages, which means that not only to get a formal definition of complex systems is hard, but also a general understanding of complex systems has not existed yet. There are some reasons. Firstly, researchers tend to be limited by specific disciplines they devote in when defining complex systems. The second is that there is a lack of special motivations and purposes when describing complex systems. As well as, a complex system is always too large to effectively explain. The defining approaches lies in the following two classes: by briefly introducing in natural languages and by listing all attributes that can distinguish other kinds of systems. By reviewing on the definitions of complex systems, this paper forms a general and wide-covered understand of complex systems using the two kinds of defining ways.

For the same instincts of complex systems, a general understand and character of complex systems can be abstracted

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from plenty of definitions and descriptions by researchers from various specific domains. Therefore, this paper reviews the descriptions of complex systems comprehensively, makes an abstract of them, gives a well-covered description of complex systems.

Mitchell, Crutchfield and Newman from Santa Fe Institute (SFI) states the central goal of the sciences of complex systems that is to understand the laws and mechanisms by which global behaviors can emerge from the collective activities of interacting components[2]. They also think the most of highly-structured collective behaviors emerge over time from the interaction of simple subsystems[3]. Complex systems are regarded as a group or organization which is made up of many interacting parts. In such systems the individual parts, called ”components” or ”agents”, and the interactions between them often lead to large-scale behaviors which are not easily predicted from a knowledge only of the behavior of the individual agents[4]. Such collective effects are called emergent behaviors. In everyday parlance the term “complex” is generally used to describe a thing that consists of many interacting components whose behavior and/or structure is just plain hard to understand. In [5], Casti from SFI lists the identifying features separating complex systems from other kinds of systems: instability, irreducibility, adaptability and emergence. He considers “emergent properties” as the single most distinguishing feature of complex systems.

Y. Bar-Yam from the New England Complex Systems Institute (NECSI) says studying complex systems cuts across all of science, as well as it focuses on certain questions about relationships and how they make parts into wholes. In [6], he describes three interrelated approaches to the modern study of complex systems; (1) how interactions give rise to patterns of behavior, (2) the space of possibilities, and (3) the formation of complex systems through pattern formation and evolution. Baranger in NECSI tries to convey the meaning of complexity by enumerating the most typical properties as followed[7]: (1) Complex systems contain many constituents interacting non-linearly. (2) The constituents of a complex system are interdependent. (3) A complex system possesses a structure spanning several scales. (4) A complex system is capable of emerging behavior. (5) Complexity involves an interplay between chaos and non-chaos. (6) Complexity involves an interplay between cooperation and competition.

In [8], dynamics of distributed networks is regarded as a central focus of complex systems which treats a complex system as a huge network. In the perspective of networks, each node represents a state variable with a given value; each node in a network tries to select the value that optimizes its own utility while maximizing its consistency with the influences from the other nodes. Simon from Carnegie Mellon University introduces some principals of a complex system which are conducive to an ability to perform complex functions[9], including homeostasis, membranes, specialization, near-decomposability, special mechanisms for dealing with chaos, etc.

Shalizi from the Center for the Study of Complex Systems, University of Michigan, discusses a complex system as one with many parts, whose behaviors are both highly variable and strongly dependent on the behavior of the other parts[10]. In the center, the research of complex adaptive systems contributed by John Holland is also an important aspect of complex systems.

Heylighen from the ECCO institutes of Vrije Universiteit Brussel has described that complexity characterized by many distinctions and connections, is situated in between disorder (many distinctions, few or no connections) and order (many connections, few or no distinctions)[11]. He denotes it is a common observation that complex systems have a nested or hierarchical structure: they consist of subsystems, which themselves consist of subsystems, and so on, until the simplest components, elementary particles[12]. In his articles, self-organization and evolution are not distinguished strictly, because he thinks both are processes that spontaneously take place in complex systems and that generate more complexity. Finnigan from the Centre for Complex System Science, Australia, thinks two properties: self-organization and emergence set a complex system apart from others[13]. Calvano and John conclude the items often using to define complex systems as[14]: elements (and their number); interactions (and their strength); Formation/Operation (and their time scales) diversity, variability; environment (and its demands); activity(ies) [and its (their) objective(s)]. Complexity is related to the amount of information needed to describe the system [15] and is also a function of the number of (unique) elements in the system as well as the number and nature of their interconnections[16].

In the reference [17], complex systems are defined as systems which are capable of exhibiting complex phenomena, as well as phenomena which are somewhere between the regular and the random are called complex phenomena. The authors of [18] take a complex system to be characterized by a collection of many interdependent parts that interact with each other through competitive nonlinear collaboration leading to emergent, self-organized behavior. The paper [19] emphasizes that realistic complex systems are characterized by a multi-level structure. Keating describes that a complex system comprised of multiple embedded and interrelated autonomous complex subsystems, is one of subsystems in an integrated meta-system[20]. Lecerf and Nguyen defines that a complex system is composed of a set of components, each of them being itself a set of sub-components, in which various interactions between different organization levels take place, as well as recurrence or hierarchy is the most fundamental characteristic of complex systems[21]. In [22], complex systems, comprised of a large number of interacting and coupling entities, have nonlinear behavior and cannot simply be derived from summation of analyzed individual component behavior. The [23] characterizes complex systems using following items: (1) composition of multi systems and (2) nonlinear multi time-varying systems. A complex system is a ”system of systems”, which means relationships among subsystems won't be unchangeable, distinguishing from large-scale systems proclaimed in 1960s who's structures are stable.

2) Perspective-Based Classification: In conclusion, the definitions and descriptions we discussed above come from different points of view including the Agent-Based Perspective, the Network-Based Perspective, the System-Of-Systems Perspective and the Evolution-Based Perspective.The properties, emphasized highly in all perspectives, are self-organization and emergence that always are regarded as identifying features distinguishing from complicated systems or simple systems. The opinions on the generating mechanisms and processes of self-organization and emergence make the rules for dividing all views of definitions into different perspectives.

The Agent-Based perspective focuses on the understanding of constituents of complex systems. By the perspective, constituents of a complex system are defined as agents, who are independent entities with active and autonomous behaviors, have strong or weak interactions among each others from which collective behaviors or emergent properties emerge. The perspective tends to study emergent attributes of a complex system by analyzing and modeling the structures or behaviors of agents who set up the system.

The Network perspective takes complex systems as networks in which components are represented nodes, interactions among components are connections or arcs between nodes, and values/weights on arcs are strength of interactions. In this kind of perspectives, the first issue has to do with the connectivity properties of networks[24]. The point of view thinks that a system is a information-processing group or organization, as well as a complex system is a kind of large scale and highly-structured networks. Complexity may come from different sources: topological structure, network evolution, connection and node diversity, and/or dynamical evolution[25]. By the description, many natural and human society systems can be characterized by networks, such as human brains, immune systems, swarms and etc. And the information-processing ability of a network as a whole indicates the emergent behaviors.

The System-Of-Systems perspective developing traditional analysis and modeling approaches concentrates on hierarchical structures of complex systems and describes a complex system in a recurrent way. According to the thinking, emergent properties of a complex system are treated as system goals or behaviors generated by lots of subsystems together. A system of systems is open at the top, open at the bottom, and continually but slowly changing[26]. An additional and essential aspect of a system of systems perspective is the recognition that every system is embedded in an environment or a larger system[20].

The Evolution-Based perspective views evolution in a complex system as a specialization of emergent properties emerging from the dynamics and interactions among constituents of complex systems. The critical concept is that components keep adaptive to the small environment then live in and the whole system adapts to its environment. In the point of view, the formation of complex systems comes from a couple of simple ”modules”, which means that more complex systems are generated from those modules through continuously evolving.

By reviewing the points of view from all kinds of researchers, this article lists some elementary concepts for defining a complex system: elements/ components/ agents/ constituents, interactions, emergent/ collective/ global behaviors, self-organization, evolution, adaptation, etc. To describe complex systems, there are some constraints or requirements adding to the concepts. The number of components is large. The type of interactions characterized by non-linearity is of variety and diversity. The whole functions of a system mainly relay on interactions among components, and belong to emergent behaviors which cannot be reduced from components. All the concepts defining a complex system in quality set complex systems apart from simple systems, nonlinear systems, large-scale systems, etc.

In this paper, we draw an conclusion of the general understanding of complex systems. A complex system:

- Characterized by hierarchy and network;
- Is composed of large interaction components;
- And the interactions are of variety and diversity, as well as the non-linearity is a main paradigm of the interactions;
- And the main goals and functions are included in the emergent behaviors;
- In which self-organization, adaptation, evolution can be conceived.

3) Emergence: It has been discussed many times that the essence of complex systems lies in the emergence of complex structures from the non-linear interaction of many simple elements that obey simple rules[27]. Emergence as the most critical concept declared in the research domain denotes the principle that the global properties defining higher order systems or ”wholes” can in general not be reduced to the properties of the lower order subsystems or ”parts”[19]. Interactions among components are the basis of self-organization, evolution and adaptation. Furthermore, evolution can be regarded as a most common kind of self-organization. Probably the most pervasive example of self-organization is biological evolution[13]. When choosing different boundaries to distinguish a complex system and its environment, adaptation is equivalent to self-organization[28]. In this paper, emergence and other emergent properties are introduced as important concepts in complex systems.

According to the basic descriptions of the science of complexity and complex systems, emergence arises from the non-linearity of interacting behaviors among components. In the science of complexity, complex phenomena are often considered as instances of some emergent higher-order structure[29], which indicates the idea of emergence generating by the lower-level dynamics. Emergence is a phenomenon that can exist across many scales of organization, ranging from the microscopic (atoms and molecules) to the macroscopic (organisms, species and ecosystems)[30].Emergent behaviors are often characterized by the recurrent and recognizable events observable in a system’s macro-scale environment, which result from simple local interactions between system components[31]. Emergence refers to the arising of novel and coherent structures, patterns, and properties during the process of self-organization in complex systems[32]. Emergent phenomena are conceptualized as occurring on the macro level, in contrast to the micro-level components and processes out of which they arise[32].

Emergence requires systems with at least the following characteristics (in spite of potential confusion caused by the heterogeneous vocabularies and methodologies of the diverse sources of emergence, there are certain ideas that cut across them)[32]: 1. Non-linearity; 2. Self-organization; 3. Beyond equilibrium (multi-, non-, or far from equilibrium); 4. Attractors.

The concept of emergence (emergere, lat.: to appear, being produced, come into existence) has been known to the ancient Greek already and can be found throughout a large number of scientific fields, e.g. psychology, biology, physics and many more. The best-known definition of emergence is that "the sum is more than the whole of its parts". In the context of self-organization this means that the behavior of a system as a whole[33], [34]

- arises from the interactions of its parts,
- seems not to resemble to the behaviors of its parts,
- is substantially more complex than the behavior of its parts.

Yet the exact the meaning of the term emergence (what is described by Emergence) has been strongly disputed in the scientific community. At the moment two directions of interpretation can be identified[33]:

- Emergence cannot be explained
- Emergence can be explained

Until now, an understanding of emergence is that a system's behavior cannot be reduced to the behavior of its parts[35]. Emergence denotes no longer the "gap" but the connection between micro and macro level. Emergent properties are ones that arise due to the interactions in a system, and are not inherent in the individual components. Emergence is related to identifying the "cause" of higher-level phenomena with respect to a lower-level framework.

Basic emergence then refers to a property or structure or behavior of the system that can be produced by interactions of its agents (components) with each other and with the environment and cannot be produced by summing behaviors of individual agents in the environment. Emergence is a classical concept in complex system theory[36]. Under certain conditions or from various angles, interactions among components can generate self-organization, adaptation, evolution, and other emergent properties who are observed on the system level or higher level.

Emergence indicates the innovation of complex systems. Heylighen says that An emergent property will typically constrain the behavior of the lower level components[28], which means that the behaviors of the lower level components won't affect the higher or highest level emergent behaviors directly. What people concern most is emergent properties that are sometimes represented in the form of system goals or functions. Consequently, it is important for adjusting or changing system goals under given constrains to make clear the emergence mechanisms of system goals or emergent behaviors. In other words, emergence mechanism of a emergent property exhibits the generating process of the emergent property accomplished by corresponding components and interactions, which helps a controller to construct control strategies for controlling system behaviors.

4) General Properties: This article takes with regard that self-organization, adaptation, evolution, known as general emergent properties of complex systems, are instances of emergence in a system. Complex systems are non-equilibrium systems displaying self-organization, and the collective properties of these systems are complex emergent properties[30].

The combination of structure and emergence leads to self-organization, which is what happens when an emerging behavior has the effect of changing the structure or creating a new structure[7]. Self-organization is concerned by the internal structure of a system, and how that structure evolves/changes without external intervention. A system described as self-organizing is one in which elements interact in order to achieve a global function or behavior[37]. This function or behavior is not imposed by a single or few elements, nor determined hierarchically. A general characteristic of self-organizing systems is that they are robust or resilient[28]. Self-organization implies a functional structure existed that can maintain itself[38].

Halley and Winkler have stated that two fundamental concepts in complex systems science are emergence and self-organization[30]. Many systems in the natural world are self-organized and exhibit emergent behavior. Self-organization and emergence are intimately related, and the work contributed in Reference[30] is to describe how emergence may be characterized in terms of self-organization[30].Perhaps the single most important characteristic shared by all complex systems is self-organization that can be described as the spontaneous appearance of large-scale organization through limited interactions among simple components[39]. When the complexity of a systems had been accumulated enough, self-organization would happen spontaneously/autonomously for improving the efficiency and effectiveness of the system[40], [41]. Paczuski and Bak denote that complex systems must be situated at this delicately balanced edge between order and disorder in a self-organized critical state[42]. Reference [30] defines self-organization as a dissipative non-equilibrium order at macroscopic levels, due to collective, nonlinear interactions between multiple microscopic components.

Nobel prize winner Lehn suggested that SO and SA (self-organization and self-assembly) could be distinguished on a thermodynamic basis[30]. Self-organization implies non-equilibrium. Self-assembly reserved for processes tending toward equilibrium. Self-assembly is a non-dissipative structural order on a macroscopic level that is due to specific interactions among (usually microscopic) components. This order is encoded in the rules of interaction and does not require an energy source[30]. As systems become more complex (the emergence continuum moves further towards the complex emergence extreme), self-organization appears at more than one level, possibly through repeated symmetry breaking bifurcations[30].

Self-organization implies adaptation, if we choose a different boundary to distinguish system from environment. Evolution is the process of learning about effective solutions, occurs through direct feedback from the environment. Evolution is the adaptation of populations through inter-generational changes in the composition of the population.

B. Controlling Complex Systems

Complex system control (CSC) has been a hot research domain concerned by more and more researches. Its principal distinct to traditional control is that complex system control tries to calibrate or generate emergent phenomena that tend to satisfy control goals. According to the elementary characters we talk about above, it's clear that complex systems are set up on large scale components and nonlinear interactions among them, as well as system functional behaviors are of emergent properties[23] . Emergence mechanisms explain the relation between emergent behaviors and, components and interactions in a certain range. Generally, control of complex systems functions on the basis of emergence mechanism by changing some components' behaviors and/or system structures (called system restructuring and calibration).

As known above, the general emergent properties include self-organization, adaptation and evolution, in which self-organization is treated as the core attribute, because that self-organization implies adaptation and evolution from alternative perspectives. By wide-accepted understanding, self-organization is a process that interacting components generate some kind of system goals without external intervention.

To control a complex system, it is should be taken into consideration that self-organization. The mapping relation between general properties and control methodologies with respect to components and interactions is shown in Figure 1, in which emergence is a comprehensive term, as well as all specific control methods can be integrated into a universal control methodology that will be introduced in detail later.

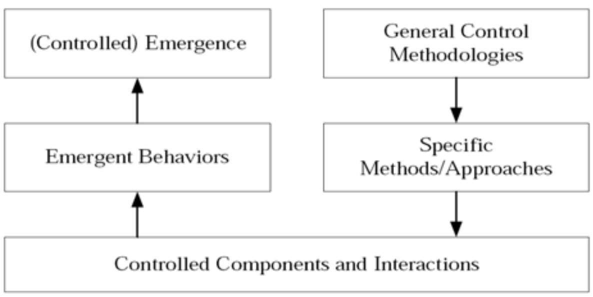

Fig. 1. Mapping Model of CSC and General Emergent Properties

The general properties as emerging phenomena of complex systems provide a principal way to understand the essence of complex systems. The premise for controlling a complex system is to make clear emergence mechanisms of the system behaviors relating to control goals. Basing on attributes of complex systems and emergence mechanisms, different kinds of control of complex systems is formed, such as self-organization control, adaptive control, and so on. Control methods for a specific system deal with some kind of emergent behaviors by its emergence mechanism too.

In conclusion, this paper gives the general characteristics of control of complex systems as following. Firstly, control strategies are determined by emergence mechanisms and system behaviors, as well as the second is that control is a process open dynamic cooperating control strategies to system behaviors.

In conclusion, control of complex systems is not belong to traditional control. From the perspective of universal definition of control, this article treats complex system control as a branch of system control, which extends and develops the existed control theories and methods to/in complex systems. Control methods of complex systems are distinct obviously when facing different kinds of specific applications. Based on general requirements of controlling complex systems, the control are viewed as a self-organization process changing system behaviors in given ways.

C. Conceptual and Methodological Issues

In general, the study of complex systems needs more work contributed by researchers, as well as some conceptual and/or methodological topics as following should be treated correctly at the current phase in the research domain.

Firstly, how the essential character of complex systems is defined or described in a formal way? That is, although many researchers focus on different aspects of various kinds of specific complex systems, a common essence is needed to be stated completely. In the paper, it is emergence that is treated as the core concept of complex systems. Secondly, can a universal control methodology that can contain existed control approaches for specific systems be found? Actually, there has been many control methods introduced to specific systems by researchers and engineers. According to the essence of complex system theory, they can be viewed as metaphors of the universal methodology in every specific field. And the universal methodology presents the common idea for controlling complex systems, which means it integrates the general ontology of complex systems into elementary control paradigms.

The issues are the hot point in complex system theory and complex system control that be emphasized and discussed in the paper.

III. Understanding Emergence

Greek philosopher Aristotle two millennia ago captured the concept as "the whole is something over and above its parts, and not just the sum of them all"[43]. In complex system theory, emergence is looked as the key to understand complex systems. Emergence still lacks a clear, standard and widely accepted definition.

As stated before, emergence is the most important concept in complex system theory, as well as the just feature when distinguishing complex systems from other ones. In this paper, the concept Emergence is treated as the core property of complex systems, as well as is described as the highest abstract level in the theory of complex systems. Emergence can be viewed as any phenomenon (emergent behaviors and/or properties) observed at system level including emergent properties and emergent behaviors. Emergent properties are divided into tow categories called general properties and other properties respectively. General properties are self-organization, adaptation and evolution that can be met in any complex system. Other properties and emergent behaviors mean that their identification relies on specific systems.

For the on-going discussion, we give a linguistic definition about emergence.

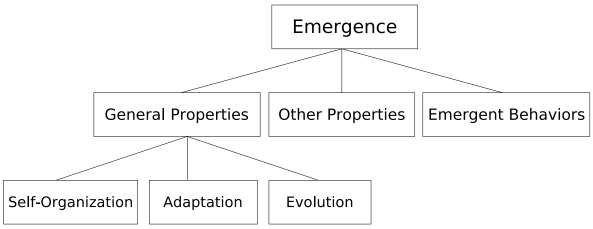

Fig. 2. Emergence's Structure

Emergence is the macro level phenomenon generated by (not reduced to) large-scale micro level components and non-linear interactions among them.

As the core property, emergence is viewed as the key to understand complex systems. That is to say, understanding emergence implicates understanding complex systems in some ways. It is one of hot issues that to explain how higher-level system behaviors are generated from lower-level constituents/entities.

Essentially, an emergence can be interpreted as a system behavior in system theory, because the two concepts are all used to define a kind global phenomenon or process exhibited by a system. So, it can be explained generally by describing the correlation/correspondence between emergence, and components and interactions among them in constituent-level.

Before general understanding delivered, some terms need to be predefined to divide different levels (system- or constituent-) in a system. When it comes to definitions of complex systems or emergence, the terms, such as "constituents/components" and "global/collective systems", "lower-level individuals" and "higher-level whole", "sub-systems" and "systems", are used frequently. One of characteristics of complex systems is hierarchy which is denoted in the perspective of "System-Of-Systems". Therefore, one system can be viewed as it is composed of its sub-systems, which themselves are composed of sub-systems, and so on, until the tiniest particles we know. Actually, we haven't to do that. When we study on a specific system, the question how many abstract-levels we need is dependent on our research goals. Such as, some physicians care about more smaller particles than the smallest ones we have known; and economists think that people and/or companies are at the lowest level in economy systems.

So, this paper uses "constituent sub-systems" and "system" to represent the two abstract levels, which is subject to the goal that is to explain the forming process from the lower level to the higher level.

A. Constituent Subsystems

As stated above, constituent sub-systems are regarded as the elementary components when talking about emergence-related concepts. Actually, methodologies and thoughts that try to understand emergence in complex systems are all starting with illustrating the concepts from constituent-level. The following content constructs the concept cluster on constituent-level by defining states, state space, behaviors, interactions, etc. of/among constituent sub-systems, which provides the basis for the concept-defining on system-level and understanding emergence.

A (internal or external) constituent sub-systems of a system is marked as "c"; and "C" is a set of constituent subsystems. "$\mathcal{C}$" represents a set of the constituent sub-systems from a system and its environment that take effect on forming of certain system behavior.

1) States: In classical mechanics state of a system (or body) refers to its condition at a particular moment of time; thus the terms initial state, reference state etc. In thermodynamics/statistical mechanics, a thermodynamic state, or more precisely, a macro state, is the specification of a particular combination of physical properties (e.g. temperature, volume, pressure, etc). a micro state is a detailed description of a collection of atoms or other particles. There may be many micro states corresponding to the same macro state. A state is the complete set of properties. A physical property is any aspect of an object or substance that can be measured or perceived without changing its identity.

In system theory, a state is an aggregated value of all state variables of a constituent sub-system at one moment. A state variable is an element of the set of variables that describe the state of a constituent sub-system. "State space" refers to the space whose axes are the state variables. The state of a constituent sub-system can be represented as a vector within that space. A property is an identifiable characteristic of a constituent sub-system that is subject to being measured.

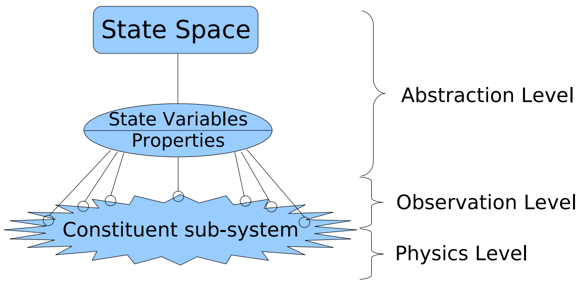

Fig. 3. Formation of the State Space of a system

The state-space of a constituent sub-system (c) is marked as $\mathbf{O}$, or $\mathbf{O}_c$.

$$\mathbf{O}_c = \{\xi | \xi = (\sigma_1, \sigma_2, \cdots, \sigma_n)\}, n \geqslant 1 \quad (1)$$

where, ξ or ξ^c represents one state of c; σ_i is the i^{th} state variable(Property or Attribute); and n is the degree of the state space.

As shown in Fig. 3, "$\mathbf{O}$" of a constituent sub-system is the space constructed with σs as dimensions. And the "σ"s are both of the constituent sub-system and its environment, which shows that not only the membrane of a complex system is hard to recognize, but also the openness is one of characteristics of complex systems. More importantly, system states are determined by the internal and external factors of a constituent sub-system.

2) Behaviors: From numerous definitions of complex systems, we know that constituent sub-systems' behaviors determine collective system behaviors directly following some

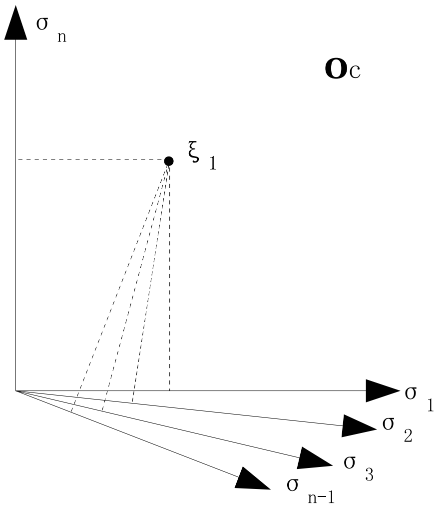

Fig. 4. The state space of a constituent sub-system

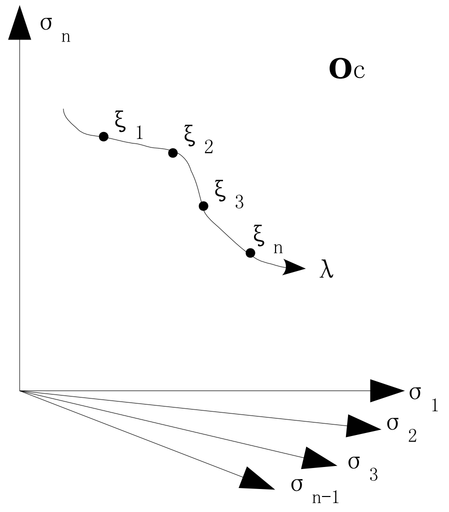

Fig. 5. One behavior's trajectory in the state space of a constituent sub-system

rules, which implies to define constituent sub-system behaviors is necessary for explaining collective behaviors. The behaviors can be described by using states and the state space of a constituent sub-system. More detailedly, a behavior, referring to continuous changing of states is represented as a trajectory in the state space of a constituent sub-system. According that, we deliver the universal definition of behaviors of a constituent sub-system.

a) Actions: Obviously, the changing process of states of a constituent sub-system is continuous. For observers, the process is conceived in a discrete way. So, for the consistency when it comes to changing of states, we define actions of a constituent sub-system. It is stated as that one action is the changing process of one state to another. In other words, it only needs to determine the initial state and the terminal state when defining an action.

One action (marked as "ι^c")of a constituent sub-system "c" is represented as following.

$$\iota = \iota^c(\xi_i, \xi_j) = < \xi_i \Rightarrow \xi_j > \quad (2)$$

where, ξ_i represents the i^{th} state of c, $\xi_i \in \mathbf{O}_c$; "$\Rightarrow$" means "transits" or "converts to".

b) Behaviors: As stated above, in the state space of a constituent sub-system, one behavior is equal to a trajectory, as well as it can also be a sequence of some actions.

One behavior (marked as "λ^c") of a constituent sub-system is:

$$\lambda = \lambda^c = \int \iota = < \cdots \Rightarrow \xi_{n-1} \Rightarrow \xi_n \Rightarrow \cdots > \quad (3)$$

where, $\lambda or \lambda^c$ represents one behavior of the constituent sub-system c; ξ_i is the i^{th} state of the constituent sub-system c.

The behaviors space of a constituent sub-system is taken as the complete set of behaviors, marked as Λ, or Λ_c.

$$\Lambda = \Lambda_c = \{\lambda\} \quad (4)$$

3) Interactions: Emergence is from interactions among constituent sub-systems in a complex system. That is to say, collective behaviors relay on interactions. In complexity science, non-linearity is viewed as the source of complexity, that is exhibited by interactions among constituent sub-systems in complex system theory. So, it is interactions that determine system behaviors of a complex system.

Interactions illustrate there is inter-effect among constituent sub-systems. In other words, states of one constituent sub-system can be changed not only by itself, but also by other ones through interactions. In conclusion, an interaction represents the relationship between two constituent sub-systems.

The interaction (marked as "r") between two constituent sub-systems (c_a,c_b) is:

$$r = r(c_a|_{\xi_i}, c_b|_{\xi_j}), \xi_i \in \mathbf{O}_{c_a}, \xi_j \in \mathbf{O}_{c_b} \quad (5)$$

where, ξ represents one state in its state space $\mathbf{O}$; $\mathbf{O}_c$ is the state space of a constituent sub-system c.

As shown in Eq.5, "r" represents the effect "c_a" taking on "c_b" subject to its state "ξ^{c_a}", and the effect "c_b" taking on "c_a" subject to its state "ξ^{c_b}". Consequently, the two states are changed. The process is shown as: $(\xi_i^{c_a}, \xi_j^{c_b}) \xrightarrow{r} (\xi_{i+1}^{c_a}, \xi_{j+1}^{c_b})$.

The interaction space (marked as $R(c_a, c_b)$) of any given two constituent sub-systems ($c_a, c_b \in \mathcal{C}$) is the complete set of interactions between the two constituent sub-systems.

$$R(c_a, c_b) = \{r(c_a|_{\xi_i}, c_b|_{\xi_j}),\} \quad (6)$$

where, $i = 1, 2, \cdots, n; j = 1, 2, \cdots, m; c_a \neq c_b$; $\sum \xi_i^{c_a}$ and $\sum \xi_j^{c_b}$ are equal to $\mathbf{O}_{c_a}$ and $\mathbf{O}_{c_b}$ respectively.

The interaction space of all constituent sub-systems (or a system) is marked as "$\Re_{\mathcal{C}}$". It is the complete set of Rs between any two different constituent sub-systems.

$$\Re_{\mathcal{C}} = \{R(c_a, c_b)|\ c_a \neq c_b, a, b = \cdots, k, k+1, \cdots.\} \quad (7)$$

where, $\sum c$ is equal to $\mathcal{C}$ which is the complete set of constituent sub-systems of a system.

B. Systems

In this paper, we try to propose a kind of universal explanation of complex systems. Generally, the term "$system$", unless emphasized, means a complex system. In this section, the concepts from system-level, such as system's description, system states, system behaviors (known as emergence), system structure, etc., are introduced systematically, based on which the correlation between proposed concepts from constituent-level and system-level is discussed.

1) Definition: First of all, a general description for defining complex systems is delivered as following. One complex system, marked as "CS", is:

$$CS = (\mathcal{C}, \mathcal{S}^{\mathrm{m}}, \mathcal{E}) \tag{8}$$

where,$\mathcal{C}$ represents the complete set of constituent sub-systems, including C_{sys}(the complete set of internal constituent sub-systems) and C_{env}(the complete set of external/environment constituent sub-systems); $\mathcal{S}^{\mathrm{m}}$ is the system structure space, as well as is the power set of $\Re$; $\mathcal{E}$ is the set of emergent/global behaviors.

The definition points out that three elementary factors of complex systems are constituent sub-systems, system structures and system emergence. Furthermore, system structures determine system behaviors. More precisely, system behaviors are determined by functional structures including existing structures and feasible structures. So, Def. 8 is equivalent to the following.

$$CS = (\mathcal{C}, \mathcal{S}, \mathcal{E}) \tag{9}$$

where, $\mathcal{S}$ represents the set of existing and feasible structures.

2) States: From the perspective of "System-Of-Systems", system states are similar to constituent sub-system's states in essence. State variables of a constituent sub-system that compose its state space can be measured directly. However, state variables of a system relay on states of the constituent sub-system from itself and/or its environment.

"State space ('X')" refers to the space whose axes are the state variables. One state ('χ') of a system can be represented as a vector within its state space. As stated above, one state variable of a system is determined from a number of constituent sub-systems' states. That is to say, a state variable ("$\Bbbk$") of a system is a function of a group of states of constituent sub-systems.

$$\Bbbk = f_{\Bbbk}(\xi_1, \xi_2, \cdots, \xi_n), \xi_i \in \mathbf{O}_{c_i}, c_i \in \mathcal{C} \tag{10}$$

where, $\Bbbk$ represents one state variable of a system; $f_{\Bbbk}$ is the producing function of a state variable "$\Bbbk$"; ξ_i is the current state of constituent sub-system "c_i".

Especially, it is relies on information of specific systems that to obtain producing functions of themselves state variables.

A system state ("χ") at one moment is represented as a vector of state variables.

$$\chi = \{\Bbbk_1, \Bbbk_2, \cdots, \Bbbk_m\} \tag{11}$$

where, "m" means the degree of the state space or the amount of state variables.

The state space ("X") of a system is a complete set of system states.

$$\mathrm{X} = \{\chi\} \tag{12}$$

3) Behaviors: As defined above, emergence refers to any phenomenon that can be observed at system level. As well as, we call phenomena exhibited within a system "system behaviors" in the paper. Therefore, we focus on defining system behaviors (that is emergence) in this section. A system behavior, referring to continuous changing of states is represented as a trajectory in the state space of a system.

For system observers, the continuous state-changing process can only be conceived in a discrete way. So, for the consistency when it comes to changing of states, we define actions of a system. It is stated as that one action is the changing process of one state to another. In other words, it only needs to determine the initial state and the terminal state when defining an action. An action of a system is marked as "η" described as following.

$$\eta = \eta(\chi_i, \chi_j) = < \chi_i \Rightarrow \chi_j > \tag{13}$$

where, χ_i represents the i^{th} state of a system, $\chi_i \in \mathrm{X}$; "$\Rightarrow$" means "transits" or "converts to".

As stated above, in the state space of a system, one behavior is equivalent to a trajectory, as well as it can also be a sequence of actions. One behavior of a system, marked as "ε", is as following.

$$\varepsilon = \int \eta = < \cdots \Rightarrow \chi_{n-1} \Rightarrow \chi_n \Rightarrow \cdots > \tag{14}$$

where, χ_i represents the i^{th} state of system, $\chi_i \in \mathrm{X}$; "$\Rightarrow$" means "transits" or "converts to".

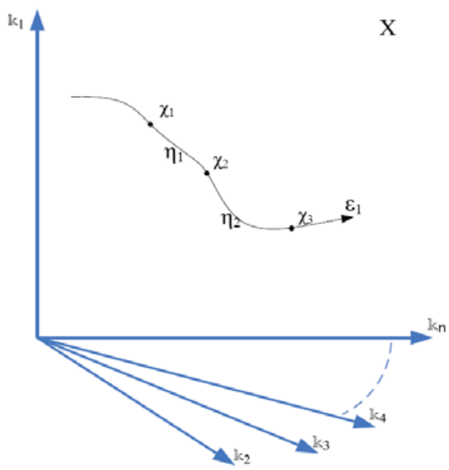

Fig. 6. One behavior's trajectory in the state space of a system

The complete set of system behaviors of a systems is "$\mathcal{E}$":

$$\mathcal{E} = \mathcal{E}_{CS} = \{\varepsilon\} \tag{15}$$

As known, system emergence is from constituent sub-systems and interactions among them. Furthermore, there isn't one-to-one correspondence between a system behavior and a number of interactions. That is to say, the same constituent sub-systems and interactions can generate different system behaviors. For this reason, we name the set of this kind of system behaviors as similar-structured emergence ("E^{Δ}"):

$$E^{\Delta} = \{\varepsilon | \forall \varepsilon_i, \varepsilon_j, \varepsilon_i \triangleq \varepsilon_j, \varepsilon_i, \varepsilon_j \in \mathcal{E}\} \tag{16}$$

where, $E^{\Delta} \subset \mathcal{E}$.

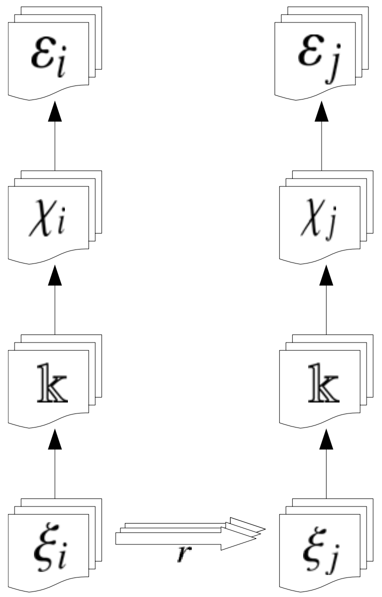

Fig. 7. Process of forming and changing emergence from interactions

4) Structures: Structure is the type of connection between the elements of a whole[44]. It has its own internal dialectic. Wholeness must be composed in a certain way, its parts are always related to the whole. It is not simply a whole but a whole with internal divisions. Structure is a composite whole, or an internally organized content.Structure is an extremely abstract and formal concept. Structure is actually the law or set of laws that determine a system's composition and functioning, its properties and stability.

System structure (marked as "s") of a system is the overview of interactions among internal and/or external constituent sub-systems, that is the topological description of the complete set of interactions.

$$s = \{r_1, r_2, \cdots, r_i, r_j, \cdots, r_m\}. \tag{17}$$

where, $r_i \in R_i \cup r_j \notin R_i, m \leqslant |\mathcal{S}|$.

The interaction space (See Def.7) of a system is the set of Rs between any two different constituent sub-systems. The structure space of a system is the complete set of structures.

$$\mathcal{S} = \{s\} \tag{18}$$

In addition, $\mathcal{S}^m$ is the power set of $\Re$s, that is a set of all subsets of $\Re$; $\mathcal{S} \subset \mathcal{S}^m$.

Fig.8 shows the main concepts in constituent- and system-levels, and their relationships. Those terms systematically define a formal way to describe the elementary concepts from constituent-level to system-level. By this way, this paper discusses the core concept in complex systems – emergence, and its formation from constituent sub-systems.

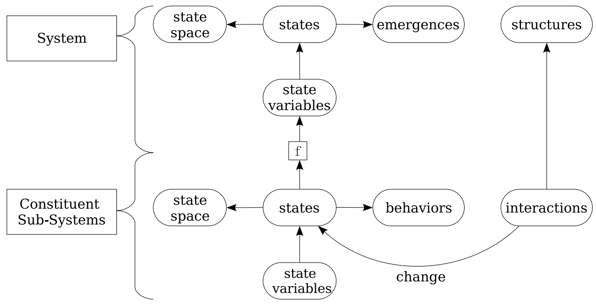

Fig. 8. Overview of concepts from constituent- and system- levels

C. Theory on Dealing with Emergence

Based on the above-stated concepts on constituent- and system-level, the paper creates the correlation between the two abstract levels, which aims at explaining the forming process of system behaviors and its dynamics. Essentially, the task of understanding emergence is to formally define the process.

It is to define the forming process of system behaviors that not only explains the correspondence of the concepts from system- and constituent- levels but also provides a self-contained concept system for modeling, analyzing and control of complex systems.

1) Emergence Mechanisms: An emergence mechanism maps a kind of system behaviors to some components and interactions among them. Describes the relation between higher level phenomenon and lower level elements.

An emergence mechanism ("ω") of a system behavior ("ε") is the rules and laws to generate the ε subject to a system structure ("s"). That is to say, in a system structure, an ω is capable of completely determining and explaining the corresponding ε by describing the degree and existence of interactions among constituent sub-systems in a certain range.

$$\omega = \omega_{\varepsilon} = \{\delta(r_i), i = 1, 2, \cdots, n\} \tag{19}$$

where, $\delta(r)$ represents the connection strength of interaction r; "n" is the amount of elements in one certain "s". It is the determination of connection strength "'δ' that depends on its description in specific systems.

From Eq.19 and Eq.17, one of system structures, named as "s", is viewed as the set including $r_1, r_2, \cdots, r_n$ - that is to say, "s" at a certain moment is denoted as $\{r_i,\ i = 1, 2 \cdots, n\}$. From Fig.8 and Def.5, we know that interactions among constituent sub-systems change their states. Consequently, state variables of a system is determined according to their producing functions, as well as one state of the system is changed to another, which defines corresponding system behaviors called similar-structured emergence (see in Eq.16). In conclusion, system structures depict existence of interactions in a system. And, a producing mechanism "ω" of an emergence describes the connection strength of the interactions in a system structure.

As stated, the relationship of a ε and its ω, a function of s, is as following:

$$\omega_\varepsilon \rightarrow \varepsilon \quad (20)$$

$\Omega = \{\omega\}$ is a finite set of ω; $\Omega^\triangle$ is the producing mechanism set of a set of Similar-Structure system behaviors, $E^\triangle$. $\Omega^\triangle \rightarrow E^\triangle$.

Emergence Mechanisms, in a word, point out that system emergent behaviors relay on interactions among constituent sub-systems, as well as represent the generating process of system behaviors clearly and an approach for further research on complex systems.

2) Emergence Attractors: Subject to the aim of presenting the dynamics of emergence, emergence attractors borrowing ideas from attractors in Chaos theory, are introduced, that refer to special states of complex systems.

the British cybernetics W. Ross Ashby[45] noted that a dynamic system, independent of its type or composition, always tends to evolve towards a state of equilibrium, more commonly called an attractor. This reduces the uncertainty we have about the system's state, and therefore the system's statistical entropy, which is equivalent to self-organization [28]. An attractor, in general, is a region of state space that "attracts" all nearby points as time passes. Attractors are of crucial importance because they capture long-term dynamic behavior of a complex system [46]. An attractor provides a lower dimensional representation of a system's dynamics, which in some ways immediately implies that there is some from of self-organization taking place. Typically, an attractor can be a point, a regular path, a complex sequence of states or an infinite sequence called a "strange attractor"[33]. All specify a restricted volume of the system's phase space. The ratio of the volume of the basin to the volume of the attractor can be used as a measure of the degree of self-organization present. This Self-Organization Factor (SOF) will vary from the total size of state space for totally ordered systems where there is maximum compression, to '1' for when there is total disorder and zero compression[47]. Interestingly, even though the physical dynamics of a chaotic system is unpredictable, there are certain aspects of the system that can be predicted, as it will always follow the path of an attractor[48].

An attractor is a state in the state space of a system that has an effecting range. If the state of a system lied in the effecting range of one attractor at some time, they would change their state towards the attractor as time passes.

$$\psi = \psi(\kappa) = \chi \quad (21)$$

where, ψ is one attractor; κ is the effecting range of ψ.

One state in the effecting range κ are named as χ^ψ. A system behavior ε, who has one state in its transiting chain naming as χ^ψ, makes the ψ as its terminal state of its transiting chain. A set of emergence attractors at one moment or a time period, marked as $\Psi(\Psi = \{\psi\})$, represents the set of functional attractors in a system at a certain temporal phase. Homo-module emergence attractors refer to those attractors who are sharing a same effecting range. And, each one in the set of homo-module attractors can be the terminal state for a system behavior. The set of homo-module attractors is marked as "Ψ^G", where $\Psi^G \subset \Psi$.

Attractors' Area of Effect (AoE) State Sub-Space of an emergence attractor ("ψ") or an homo-module attractor set ("Ψ^G"), marked as "$Æ_\psi$ or $Æ_G$", represents the set of the states locating in the effecting range of ψ (or Ψ^G), that is a subset of the state space.

$$Æ_\psi = \{\chi^\psi\} \quad (22)$$

3) Emergence Patterns: Based on above concepts, we propose Emergence Patterns to describe the whole process of formation and dynamics of emergence synthetically. An emergence patter, marked as Θ, implies the process that a system behavior is generated following its emergence mechanism and is becoming directly to its terminal state defined by the emergence attractors, which is subject to a certain system structure.

$$\Theta = \Theta_{E^\triangle} = (s, E^\triangle, \Psi, \Omega) \quad (23)$$

or

$$\Theta = \Theta_\varepsilon = (s, \varepsilon, \Psi, \omega) \quad (24)$$

where, Θ represents the emergence pattern of an Emergence ε; s means the topological relationship structure, $s \in \mathcal{S}$; $E^\triangle$ is the set of εs who are sharing the same structure s; Ψ is the set of attractors with respect to the set $E^\triangle$; Ω is the set of "ω"s which define the connection strength of the interactions/relationships in the structure "s". The law/regulation to generate the emergence $\varepsilon \in E^\triangle$ on the structure s, $\omega \rightarrow \varepsilon$.

In Def. 19, for an emergence (or a similar-structured emergence), there is the just emergence pattern to represent its (their) formation and dynamics. It is an emergence patterns that provides a complete explanation for an emergence and a feasible way for emergence analysis and emergence control of specific systems.

4) Emergence Analysis and Control: Analysis is the process of identifying a question or issue to be addressed, modeling the issue, investigating model results, interpreting the results, and possibly making a recommendation. Analysis is the process of using some kinds of methods to gain a better understanding of targets.

Emergence analysis is the process of identifying the emergence pattern of a given emergence "ε" or a similar-structured emergence set "$E^\triangle$" of a system by using some kinds of methods.

Actually,one of the goals studying on complex system theory is to find ways to promote some control approaches to make them implement given targets we want. Similarly to complex systems, the research on control of complex systems haven't reached a benchmark. However, according to the concept and basic methods of traditional control, we propose the description of complex system control by using emergence-related concepts stated above. Control of complex systems is the process of making a system achieve its target behavior (called "ε'") by using a control method("Φ") established according to the emergence pattern "Θ_ε" of a system behavior "ε", as follows.

$$\Theta \xRightarrow{\Phi} \Theta' \quad (25)$$

IV. Emergence-Oriented Control Methodology

This paper indicates the Emergence-Oriented Control (EOC) Methodology as a general methodology for controlling complex systems

A. General Process and Characteristics

In conclusion, this paper gives the general characteristics of control of complex systems as following. Firstly, control strategies are determined by emergence mechanisms and emergent behaviors, as well as the second is that control is a process open dynamic cooperating control strategies to emergent behaviors.

This paper defines the Emergence-Oriented Control methodology basing on understanding general properties of complex systems and characteristics of complex system control. EOC represents the principal and elementary concept for controlling complex systems, that describes the universal processes of control of complex systems by integrating attributes of complex systems and general process control methods. The methodology provides a instruction for further research on understanding process and mechanism of complex system control.

The EOC concerns changes of emergent behaviors caused by certain controllable system elements during control processes, by which control goals are judged. There are three approaches implementing EOC.

- **Direct Control Scheme**: On the premise of knowing emergence mechanisms, the scheme changes system behavioral by adjusting structures and behaviors of components.
- **System Re-Structuring**: On the premise of emergence mechanisms, the scheme changes system emergent behaviors by adjusting strength of interactions among certain components, as well as holding system structures.
- **System Calibration**: On the basis of emergence mechanisms, the scheme recreates interactions among certain components so as to generate new emergent behaviors that satisfy given control goals.

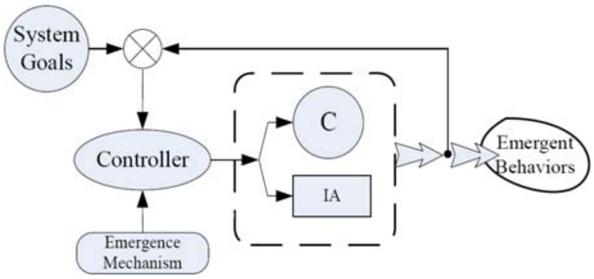

Fig. 9. General Process of CSC

Figure 9 depicts the general process of control of complex systems, in which, C means the collection of controlled system constituents, as well as IA is the interactions among them.

In complex systems, controllers treated as a kind of components, affect controlled components' structures and behaviors by interactions with them which finally changes related emergent behaviors after a self-organization process. The control process implies a guidance-based paradigm[23].

According to the key problems and general emergent properties of complex systems, the EOC is divided into three paradigms: the direct control scheme, the system structure based control scheme and the aggregated control scheme. The first scheme uses the control strategies relaying on scale or strength of emergent behaviors, and changes emergent behaviors by adjusting control strength in existing control mechanisms. The system structure based control scheme focuses on modifying the presence and strength of interactions among certain components for control goals, which bases on corresponding control mechanisms set up on emergent behaviors' mechanisms and their values. The latter concerns not only changes of control strength, but also interactions.

B. Direct Control Scheme

The direct control scheme as a special paradigm of complex system control concentrates on changes of controlled objects by which control mechanisms are established. Its control process is denoted as following equation.

$$\Phi_{DCS} = \Theta(s, \varepsilon, \Psi, \omega) \longrightarrow \Theta'(s, \varepsilon + \Delta, \Psi, \omega) \tag{26}$$

Where, Δ means that only non-structural change happens to the target emergence ε by the way of adjusting property value of some controlled components.

Controlled objects are always emergent behaviors or structures in complex systems. Therefore, control goals of the scheme are implemented by adjusting certain emergent behaviors. During control processes, it is changes of control strength that affect system emergent properties. Generally, precise models for this kind of control schemes are demanded, that are determined from accurate descriptions of controlled objects or accumulation of history datum. Figure 10 exhibits the control process of the scheme.

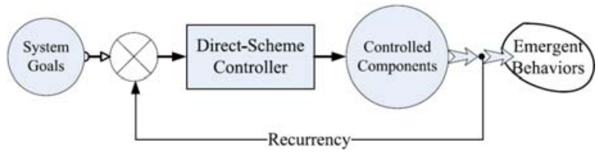

Fig. 10. Process of Direct Control Scheme

Although identifying control models are needed to be created between components on certain level and some kind of system emergent properties, the scheme is one of elementary approaches for controlling complex systems. The scheme includes the methods from classical control and modern control that are not used to control complex systems in common. This paper concludes the methods to the scheme, not only because the ideas in the methods can server the control for a special kind of complex systems, but also because the methods are an important part of the EOC methodology.

C. System-Structure-Based Control Scheme

The scheme emphasizes the ways of adjusting presence or strength of interactions to produce an effect upon system emergent behaviors, which the whole process is on the basis of emergence mechanisms.

There are two principals in this kind of control schemes. Firstly, the formation of system emergent behaviors that satisfy control goals arises from addition or cancel operations of interaction among certain components. The second is that the adjustment of interaction strength among component in a supposed range influences matching emergent behaviors. The two are called system re-structuring and system calibration respectively, that are both on the premise of emergence mechanisms.

Main functions of a complex system are subject to system emergent behaviors, as well as implementation of control relays on emergent behaviors. Furthermore, as argued above, emergent behaviors are generated by interacting components. In other words, a certain kind of emergent behaviors is produced by interactions with a fixed emergence mechanism. In conclusion, the system structure based control scheme modifies and changes interactions in order to achieve control goals, which is dependent on emergence mechanisms.

1) System Re-Structuring: System re-structuring is one of the elementary approaches for controlling complex systems, that modifies the presence of interactions according to corresponding emergence mechanisms to manufacture the emergent behaviors that satisfy control goals. It is described formally in the following equation.

$$\Phi_{SRS} = \Theta(s, \varepsilon, \Psi, \omega) \longrightarrow \Theta'(s', \varepsilon, \Psi, \omega) \qquad (27)$$

The former ε doesn't appear in the controlled system, as well as the latter ε is the goal-satisfying emergence that can be observed in the system after the control process. To the system, ε is a new-coming function or behavior.

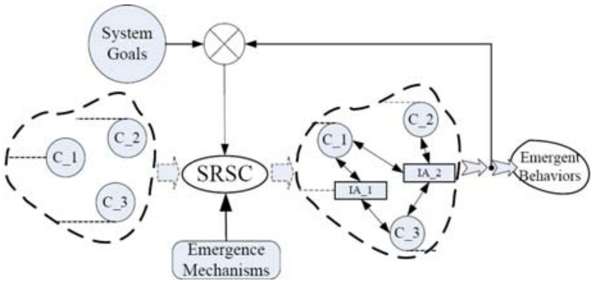

Fig. 11. Process of System Re-Structuring

The process of system re-structuring is illustrated in Figure 11 , in which $SRSC$ represents the system re-structuring controllers; C_1, C_2 and C_3 are system components in a certain range, as well as IA_1, IA_2 and IA_3 imply the interactions created by the controllers.

2) System Calibration: System calibration as one of the elementary ways of control of complex systems, changes the strength of selected interactions on accompanying emergence mechanisms so as to reach control goals, during which the system structures are hold, as shown in the following equation and figure.

$$\Phi_{SC} = \Theta(s, \varepsilon, \Psi, \omega) \longrightarrow \Theta'(s, \varepsilon + \Delta, \Psi, \omega') \qquad (28)$$

From the equation, we know that the former emergence ε is changed by adjusting its producing mechanism ω to ω'. The change of ω is to modify the connection strength of controlled interactions without adding or deleting interaction to the controlled system.

Figure 12 denotes the process of system calibration, where, SCC suggests the system calibration controllers; C_1, C_2 and C_3 are components in an assumed range, as well as IA_1, IA_2 and IA_3 are interactions among the components.

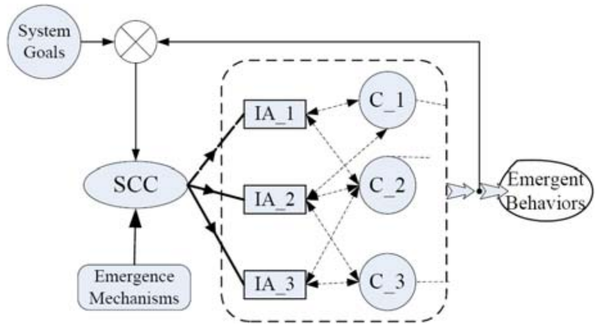

Fig. 12. Process of System Calibration

D. Aggregated Control Scheme

The scheme combines the direct control scheme and the system structure based control scheme for accomplishing control goals, as well as the process is described as following: EOC chooses one from the three principal control schemes in conformity with controlled objects, emergent behaviors and emergence mechanisms to bring out control effectiveness, which controlled components and interactions among them transfer the effectiveness for achieving control goals.

$$\Phi_{ACS} = \Theta(s, \varepsilon, \Psi, \omega) \longrightarrow \Theta'(s', \varepsilon + \Delta, \Psi, \omega') \qquad (29)$$

Obviously, Φ_{ACS} contains Φ_{DCS}, Φ_{SRS} and Φ_{SC} that implements structural and non-structural change for desired system behavior (ε).

Figure 13 depicts the process of a composed kind of control scheme, in which EOC means the emergence-oriented controllers; DSC, $SRSC$, and SCC are the direct scheme controllers, the system re-structuring controllers and the system calibration controllers respectively.

The aggregated control scheme composes the three basic control scheme reasonably providing an efficiency and useful paradigm for controlling complex systems.

V. Conclusion

Complex Systems is an approach to science that studies how relationships between constituents give rise to the collective behaviors of a system. The study of complex systems is

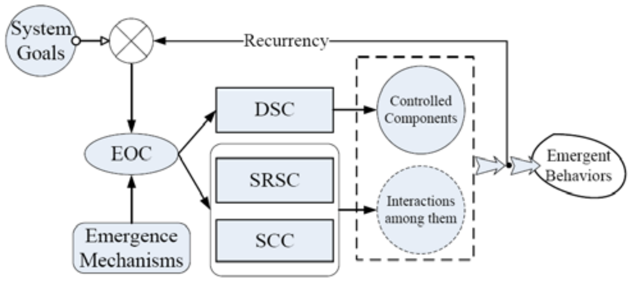

Fig. 13. Process of Aggregated Control Scheme

bringing new vitality to many areas of science where a more typical reductionist strategy has fallen short. Control of complex systems as one of important goals in complex systems not only represents the essence of complex systems, but also embodies the basic concept of control theory.

Complex systems composed of large-scale non-linearly interacting components are characterized by emergence including general emergent properties such as self-organization, adaptation and evolution, and emergent behaviors that imply system functions. Through reviewing on the properties of complex systems, this paper points out that emergence is the key to construct theoretical tools for complex systems. Consequently, a formal description for the essence concept of complex systems - Emergence, is introduced to provide a effective way to understanding the concept, as well as to begin a fresh expression in the study of complex systems. All concepts from constituent- and system- levels exhibit characteristics of systems at the two abstract levels respectively. Furthermore, emergence mechanisms, emergence attractors and emergence patterns explain the formation and dynamics of system behaviors.

By reviewing on the properties of complex systems and concepts of system control, this paper presents the key problems in control of complex systems, depicts the elementary principals for controlling complex systems as stated below. Firstly, control strategies are dependent on system behaviors and the mechanisms producing those behaviors. The second is that an efficiency control relies on not only corresponding emergence mechanism, but also controlled components and interactions among them. Consequently, the universal control concept for complex systems, called the emergence-oriented control, is indicated in the paper.

Facing the key problems in complex system control, EOC introduces three kinds of general control paradigms: the direct control, the system re-structuring and the system calibration. Correspondingly, this paper describes the control processes of three control schemes involving the direct control scheme, the system structure based control scheme and the aggregated control scheme, in which the second one consists of the system re-structuring and the system calibration that are of interaction-based scheme.

The idea delivered in the paper provides not only a universal approach to understand complex systems, but also an interdisciplinary pattern way to designing control methods for specific complex systems.

ACKNOWLEDGEMENTS

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