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Review

Large Scale Systems and Fuzzy Cognitive Maps: A critical overview of challenges and research opportunities

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ABSTRACT

Large scale systems (LSS) have been traditionally characterized by a large number of variables, nonlinearities and uncertainties. Their decomposition into smaller, more manageable subsystems, possibly organized in a hierarchical structure, has been associated with intense and time – critical information exchange and with the need for efficient and coordination mechanisms. A critical overview of the different theories and algorithms for LSS is provided. The issue of system complexity has become transparent. As the complexity of such systems increase and the presence of uncertainties play a role on the performance of LSS and HMS, new system theoretic methods become more crucial and are urgently needed. Intelligent Systems (IS) and Fuzzy Cognitive Maps (FCM) theories are such new theoretic approaches in modeling Large Scale Dynamic Complex Systems (LSDCS). An FCM is based on fuzzy logic and Neural Networks. FCM integrates the accumulated experience and knowledge on the operation of the system, as a result of the methods by which it is constructed. The new theories of FCMs are reviewed and used to model LSS and Dynamical Hierarchical Control Systems. A number of applications in using FCM to model complex systems from industrial processes economics, energy, environment, health international relations and political developments are mentioned. New challenges and research opportunities are presented and discussed.

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1. Introduction

Throughout the natural and artificial world one observes phenomena of great complexity. Yet research in physics and to some extent biology and other fields has shown that the basic components of many systems are quite simple. It is now a crucial problem for many areas of science to elucidate the mathematical mechanisms by which large numbers of such simple components, acting together, can produce behavior of the great complexity observed. As a result "complex systems theory" cuts across the boundaries between conventional scientific disciplines. It makes use of ideas, methods and examples from many disparate fields. And its results should be widely applicable to a great variety of scientific and engineering problems.

Complex systems theory is now gaining momentum, and is beginning to develop into a scientific discipline in its own right. I suspect that the sociology of this process is crucial to the future vitality and success of the field. Several previous initiatives in the direction of complex systems theory made in the past have failed to develop their potential for largely sociological reasons. One example is cybernetics, in which the detailed mathematical results of control theory came to dominate the field, obscuring the original more general goals. One of the disappointments in complex systems theory so far is that the approaches and content of most of the papers that appear reflect rather closely the training and background of their authors. Only time will ultimately tell the fate of complex systems theory. But as of now the future looks bright.

In this paper, after a critical short overview of modeling and analyzing LSS and MHS we propose a novel fuzzy neural network which equips the inference mechanism of original FCMs proposed by Kosko more than 25 years ago (Kosko, 1986) with the automatic determination of membership functions, as well as quantification of causalities. Our approach is able to identify the membership functions and causalities from real data, which makes the construction of FCM for complex systems independent of expert knowledge. Another aim of this paper is to introduce FCM to the academic and scientific communities and try to raise challenging and interesting questions related to theories and practices of the LSS and MHS. The outline of the paper is as follow: in Section 2 an overview of LSS is provided covering the most challenging issues such as stabilization and decentralized control. In Section 3 an overview of FCMs is provided covering the basic theories while the fundamentals and new proposed algorithms are given in Section 4. Section 5 covers learning algorithms for FCMs and a new algorithm that has been developed by the research team of the Laboratory for Automation and Robotics is provided and analyzed. In Section 6 the new and fast developing scientific concepts of Systems of Systems (SoS) and the Cyber-Physical Systems (CPS) are briefly mentioned and their relation to theories of LSS and MHS are outlined. Finally Conclusions and Future Research directions are provided in Section 7.

2. Large scale systems: An overview

2.1. Introductory remarks

Recently, there has been a growing interest in a class of complex systems whose constituents are themselves complex. Complexity and dynamic order of controlled engineering systems is constantly increasing. The original concept-term of Large Scale Systems (LSS) has now turned to Large Scale Dynamic Complex Systems (LSDCS) in order to accommodate the complexity and dynamic behavior of such systems. LSDCS appear in many engineering fields, such as, power systems, manufacturing, aerospace, civil and construction engineering, energy, medical, environment, transportation, agriculture as well on other non-engineering fields such as finances, business and economics, military, psychology, sociology, physiology, political and social studies and education. Modeling of these systems often result in very high-order models imposing great challenges to the analysis, design and control problems. 'Efficient Modeling and Control of Large-Scale Systems' compiles state-of-the-art contributions on recent analytical and computational methods for addressing model reduction, performance analysis, feedback control design and "optimization" for such systems. Also addressed at length are new theoretical developments, novel computational approaches and illustrative applications to various fields, along with: an interdisciplinary focus emphasizing methods and approaches that can be commonly applied in different engineering application fields. Efficient Modeling and Control of Large-Scale Systems' is an ideal volume, for the years to come, for engineers and researchers working in the fields of control and dynamic systems. The problems of dynamic modeling of large scale complex systems are considered with a view to developing reduced-order models using aggregation and decoupling. From a system-theoretic point of view, a complex dynamic network can be considered as a large-scale system with special interconnections among its dynamical nodes. The large-scale system theory has been extensively studied in the last four decades, and many interesting results have been established, on such basic issues as for example decentrally fixed modes, multilevel control, decentralized controllers design, multilevel and hierarchical stabilization diagonal Lyapunov function method, M-matrix method to mention a few. However very early in the studies of LSS, in 1974, R. Bellman had said "We need new theories of LSS. Many "new" theories and methods "analyzing" and "designed" -LSS have been developed since then, without "having" an overall and generic theory(ies) of LSS. The explanations for this are various and differ depending the needed solution for a given large complex system.

2.2. Modeling and controling Large Scale Dynamic Complex Systems (LSDCS)

2.2.1. Introductory remarks

Advances in our understanding of the traditional discipline are being made. At the same time new modes of systems engineering are emerging to address the engineering challenges of integrated embedded systems and enterprise systems. Even at this early point in their evolution, these new modes of systems engineering are evincing their own principles, processes and practices. Some are different in degree than engineering at the system level while others are different in kind. Depending the given dynamic complex system and the particular problem under consideration, a "specific problem solution" was developed.

Till the late 1960s and early 1970s the traditional approach in systems theory was to model systems in certain standard or canonical form and then design a centralized "control system". For example, the usual approach in classical as well as in modern control theory was (and still is) to transform the equations describing a given system in such a way that the system in question may be represented, for example, in the familiar block diagram form of Fig. 1.

The usual mathematical model been used has been the state model representation for Linear Time-Invariant Systems:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned} \tag{1}$$

where $x(t)$ is a $n \times 1$ state vector, $u(t)$ is the $m \times 1$ input of the system and $y(t)$ is a $r \times 1$ vector describing the system's output and the A, B, C and D are known matrices with the appropriate dimensions of the dynamic system.