Proceedings of the 11th International IEEE
Conference on Intelligent Transportation Systems
Beijing, China, October 12-15, 2008

An Investigation on ATS from the Perspective of Complex Systems

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***Abstract*—Artificial transportation systems (ATS) has been related to the study of complex systems and traffic simulation since its birth. Its relationship with complex systems and its connections, as well as differences from traditional traffic simulation systems pose an interesting problem. In this paper, according to two hypotheses about complex systems, we inferred three principles: synthesis, experimentation, and constant experimentation. We explored ATS from the perspective of complex systems, along with a diagram depicting the relationship between ATS-related concepts and methods. We then used the reasoning behind deploying agent-based modeling to explain why the principle of simple objects and relationships can be effective in ATS. We examined these principles from a complex adaptive systems perspective. Finally, essential differences between ATS and traditional traffic simulation systems are reported.**

I. Introduction

Artificial transportation systems (ATS) is an extension of the micro-simulation of traffic, proposed and initiated by Wang and Tang in 2003 [1,2]. The combined effects of other metropolitan systems, including logistic systems, social and economic systems, etc., are considered and the concepts and methods developed in the study of complex systems are also adopted in ATS. Thus it is believed to be an effective tool in the study of the integrated, coordinated and sustainable development of transportation systems [3]. Concepts and theoretical frameworks for ATS were proposed in [3] and [4].

From the brief review above, note that ATS has been related to the study of complex systems and traffic simulation since its birth. One may ask: what concepts and methods developed in complex systems form the foundation of ATS? Why is ATS logically effective? What are the essential differences between ATS and traditional traffic simulation systems? And what is ATS after all? This paper aims to discuss the topics raised by these questions and provide a conceptual understanding of ATS from the perspective of complex systems.

ATS is an investigation into modern transportation challenges from the standpoint of system theory. Metropolitan transportation systems are considered complex systems in that they involve a large number of participants, a large number of influencing factors, and the relationships among these participants and factors is nonlinear, dynamic, and hard to model precisely. Following two previous hypotheses on complex systems, it can be inferred that synthesis, experimentation, and constant experimentation are the three main principles we need to follow when facing metropolitan transportation issues. To overcome hard or even impossible difficulties and still be able to conduct field experiments with real transportation systems, artificial systems (the idea of which originated from artificial life and artificial societies) can be a more accessible, efficient, and reusable alternative for carrying out transportation experiments. The specific methods for experiments conducted within artificial transportation systems are computational experiments and parallel systems. The relationship between the above-mentioned ATS-related concepts and methods is depicted as a diagram later in this paper. The diagram also illustrates four key issues raised during the development of ATS: the modeling problem, experimentation problem, decision-making problem, and computing problem, as well as the application scenarios of computational experiments and parallel systems [3,4].

Agent-based and multi-agent systems-based (MAS-based) approaches [5,6] are being used in an increasingly wide variety of applications. A survey is provided in [7] of the research conducted on agent-based approaches to transportation and traffic management (especially focusing on freight transportation). The survey used a framework to systematically classify and access the traffic references. In particular, a lot of effort has been made to apply MAS to issues concerning microscopic traffic simulations [8-12].

Agent-based modeling is also the key technique in establishing artificial systems. Furthermore, the principle of simple objects and relationships is key when applying agent-based modeling to the design of ATS [3]. Modeling transportation participants as agents is a somewhat straightforward approach in microscopic traffic simulations because agents are a natural metaphor for humans and transportation systems fit the characterization proposed by Parunak for the ideal applications of agent-based approaches

Manuscript received July 7, 2008. This work was supported in part by the MOST Grants 2006CB705500 and 2007AA11Z217, NNSFC Grant 60621001, CAS Grants 2F05N01 and 2F07N04, and Shandong Province Taishan Chair Professor Fund.

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[13]. Despite this, agent-based modeling and the principle of simple objects and relationships can still be effective in the design of ATS. We offer a brief explanation in this paper from the perspective of complex adaptive systems (CAS).

A number of microscopic traffic simulation models or software packages have been emerging and developing over the past two decades. They have been increasingly used to assist in various transportation issues. Examples of such models include TRANSIMS[14], MATSim[15], PARAMICS[16], INTEGRATION[17], VISSIM[18] among others. The latest versions of these models and ATS have some characteristics in common. However, we believe that there are still important differences between ATS and traditional traffic simulation systems (the earlier traffic simulators).

The relationship between ATS and traditional traffic simulation systems has already been discussed elsewhere [3,4,19]. Wang and Tang pointed out in [4] that 1) a traditional simulation system can only model the local characteristics of traffic while ATS is able to model the integral characteristics; 2) conceptually, a traditional simulation system aims to approach a real transportation system, while this is not the sole nor the main objective of ATS; and 3) during implementation, the computing tools and the modeling methods that traditional traffic simulation systems often use are not suitable for modeling the object's intuition, experience, or initiatives, while ATS uses tools and methods (such as parallel, distributed, grid computing methods, agent-based modeling and object-oriented programming methods) which are more suitable for modeling the object's autonomy and the interaction between objects. In this paper, the differences between ATS and traditional traffic simulation systems are further refined in accordance with the key issues mentioned above.

The rest of the paper is organized as follows. In Section II, the relationship between ATS and complex systems is addressed, along with a diagram depicting the relationship between ATS-related concepts and methods. This section also presents an interpretation of why agent-based modeling and the principle of simple objects and relationships are used to establish ATS from a CAS perspective. In Section III, we further refine the differences between ATS and traditional traffic simulation systems. Finally in Section IV, conclusions are drawn and future works on ATS theory are discussed.

II. WHY ATS? –FROM THE PERSPECTIVE OF COMPLEX SYSTEMS

A. Metropolitan Transportation Systems are Complex Systems

Despite a lack of consensus on the definition of complex systems, there are some established general characteristics and descriptions given by researchers [20]. Using these characteristics and descriptions, metropolitan transportation systems can be categorized as complex systems according to the following arguments.

First, transportation systems usually involve a large number of participants and influencing factors, including various road users, road layouts, facilities, etc. Second, transportation systems are related to other urban systems, such as weather systems, traffic law systems, logistic systems, social and economic systems, etc. Third, the relationships between these participants, factors, and systems are complex and hard to model precisely. Here, complex is characterized by 1) that road users are autonomous, which means that they can freely create or alter their travel decisions most of the time, 2) that transportation participants are heterogeneous, which means that transportation participants can have their own personalities and differ from each other in many characteristics, and 3) that the relationships are nonlinear and dynamic.

B. Three Principles: Synthesis, Experimentation, and Constant Experimentation

Wang proposed two hypotheses about complex systems in [21].

1) As with any limited resources, in essence, the aggregate behavior of a complex system cannot be determined by the independent analysis of its components.

2) As with any limited resources, in essence, the aggregate behavior of a complex system cannot be determined on a large scale (for example, over a long period of time or within a large space) in advance.

Three inferences were also drawn based on the above hypotheses in [21].

1) Issues concerning complex systems have to be resolved from the standpoint of holism.

2) There are no general optimal solutions for the issues concerning complex systems, lest a unique optimal solution.

3) There are no one-for-all solutions for the issues concerning complex systems.

Since metropolitan transportation systems are complex systems, and following the above inferences, we can then infer three principles that need to be followed when facing transportation issues.

1) Synthesis: Utilization of holism results in the integrated consideration of all influencing factors within transportation issues, synthesis. Specifically, synthesis can be characterized in at least three aspects. First, transportation systems have to be considered as a whole rather than considered by its parts. Second, the characteristics of transportation participants have to be considered as completely as possible. Third, the combined effects and interactions with other systems have to be considered as completely as possible. From the perspective of complex systems, synthesis is not only what we do but also what we must do in order to achieve rational solutions for transportation issues.

2) Experimentation: According to the arguments presented in [21], the creation of effective rather than optimal solutions has to be accepted when resolving transportation issues. Experimentation seems obvious when considering different methods for finding effective solutions because of how difficult it is to model transportation problems mathematically in order to obtain solutions.

3) Constant Experimentation: The boundaries of real transportation problems are usually time-variant due to the dynamic characteristics of transportation systems. When the boundaries change, previously effective solutions are then inadequate and more experimentation is needed in order to cope with the new boundaries. That is the point of conducting constant experiments.

C.Deployment of the Principles

In summary, one needs to experiment with transportation systems synthetically in order to achieve an effective solution for transportation issues. Thus, conducting field experiments with real transportation systems seems to be the most direct way. However, there are four main difficulties in performing field experiments [21].

1) Intrinsic difficulty: We have to apply holism, but we usually cannot control all of the experimental conditions.

2) Economic difficulty: Field experiments often cannot be done due to high monetary costs.

3) Legal difficulty: Field experiments often cannot be done due to legal reasons.

4) Moral difficulty: Field experiments often cannot be done due to the possible risk of incurring human injuries and deaths.

To overcome these difficulties, an easy alternative solution is to experiment on an artificial transportation system established on computers which can be substituted for a real system. It is worth remarking that the idea of artificial systems originated from artificial life and artificial societies, and agent-based modeling is the key modeling technique for building artificial systems [22].

Once the artificial system is constructed, it becomes an accessible, efficient, and reusable method for carrying out transportation experiments. The specific methods for experimenting in the artificial system are computational experiments and parallel systems, which are presented in detail in [23] and [24], respectively.

What we addressed previously in this section constitutes the interpretation of the main principles of ATS from the perspective of complex systems.

D.Connections between ATS-Related Concepts and Methods in a Visual Way

In order to provide a diagram depicting the relationship between ATS-related concepts and methods, we refer to other topics on ATS besides the ones mentioned previously.

The key issues in the development of ATS are as follows:

1) Modeling problem: How to establish artificial systems.

2) Experimenting problem: How to conduct computational experiments.

3) Decision-making problem: How to construct and utilize parallel systems.

4) Computing problem: How to use new and advanced computing techniques to implement solutions for the modeling, experimenting, and decision-making problems of transportation systems.

The main application scenario for computational experiments is the behavior analysis and decision evaluation of transportation systems. The main application scenarios for parallel systems include experimentation and evaluation, learning and training, and management and control.

For more detailed information on the key issues, application scenarios for computational experiments and parallel systems, please review [3].

The relationship between ATS-related concepts and methods is depicted as a block diagram in Fig. 1.

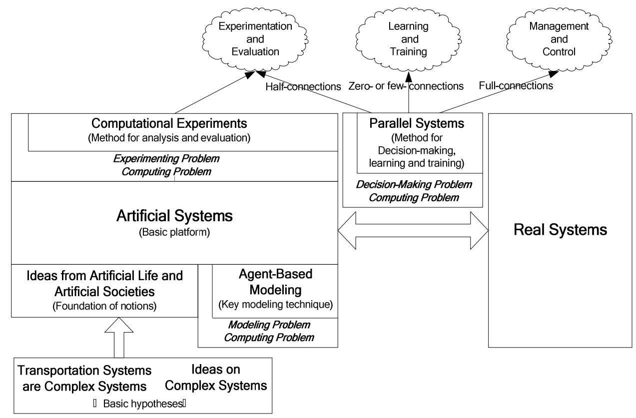

Fig. 1. Block Diagram of Relationship among ATS-Related Concepts and Methods.

It is worth pointing out that there are three types of connections between artificial systems and real systems, each of which corresponds to an application scenario in which parallel systems are in use. They are; 1) zero- or few-connections, which means that the artificial systems and real systems are not or only loosely connected, 2) half-connections, which means that they are moderately connected, and 3) full-connections, which means that they are closely connected. When artificial systems and real systems have half-connections, the application of parallel systems is that of computational experiments.

It is also worth pointing out that the solutions of computing problems form the foundation for the construction of artificial systems, computational experiments, and parallel systems, while that of the other three problems primarily supports only one ATS component.

From Fig. 1, we can also learn that, ATS is, in essence, a methodology for studying issues of metropolitan transportation systems, which consists of three components—artificial systems, computational experiments, and parallel systems. With different solutions for the key problems, we can get different versions of ATS implementation, which comprise different platforms of artificial systems, and different sets of specific methods for computational experiments and parallel systems.

E. Why Agent-Based Modeling and the Principle of Simple Objects and Relationships?—From a CAS Perspective

As mentioned above, agent-based modeling is the key modeling technique in building artificial systems. Moreover, agent models are supposed to be built upon agreeable simple objects and relationships [3]. The reason why agent-based modeling and the principle of simple objects and relationships are effective is briefly explained in this sub-section from the perspective of complex adaptive systems (CAS).

Complex adaptive systems, which were proposed by Holland et al. at the Santa Fe Institute (SFI) [25], are special cases of complex systems. A nominal definition of CAS can be found in [26].

In simple terms, complex adaptive systems are systems that consist of a large number of interacting units which can adapt themselves to a changing environment. These adaptive units are called adaptive agents, or agents. The basic principle behind CAS theory is that adaptation builds complexity. In other words, it is the adaptability of agents that makes the macroscopic behavior of systems complex.

Metropolitan transportation systems are comprised of a large number of adaptive road users in that they can make transportation decisions autonomously and alter those decisions if their travel experience is unsatisfactory. For example, an employee is likely to change his/her route to get to the workplace after he/she is late to work twice because of traffic congestion. At this point road users can be regarded as adaptive agents and transportation systems are complex adaptive systems. On the one hand road users are characterized as agents and on the other agents in CAS are suitable for modeling autonomous, active, and "live" objects. This may be a reason why agent-based modeling is used to build artificial systems in ATS.

To overcome the difficulties of reductionism, an automata network was proposed to model CAS in SFI [27]. The developers of automata networks believed that it is not the detail of each unit but the number of units that determines the macroscopic behavior of systems. In regards to ATS, this means that simple models can be used to build agents in order to observe and analyze the emergent behavior of systems. This might be why the principle of simple objects and relationships is effective in ATS from the perspective of CAS.

III. COMPARISON BETWEEN ATS AND TRADITIONAL TRAFFIC SIMULATIONS

The most frequently asked question about ATS is: what are the differences between ATS and traditional traffic simulations, especially micro-simulations. This is not surprising because an ATS platform does resemble a traffic micro-simulation platform to some degree. They both track every single traveler in traffic networks and can provide statistical analysis of system performance. Indeed, both approaches use computers to simulate traffic and assist in the analysis and decision-making of transportation issues.

However, according to the discussion above, we believe that ATS differs essentially from micro-simulations in the following ways (organized in accordance with the key issues mentioned in sub-section D, Section II).

A. Modeling aspect

1) We stress the utilization of traffic rules in object description for ATS when considering behavior generation in real traffic systems. The behavior of travelers is generated from traffic rules rather than the statistical properties of real systems or related research results.
2) In ATS, autonomy of travelers is stressed by noting whether their travels are motivated by physical, psychological, or social- and economic -related needs.
3) As for the modeling of traveler autonomy in ATS, we considered both the probability and regularity of the real world.
4) The potential impact from other urban systems on transportation systems are considered in ATS, which results in a more systemic solution when compared to the traditional simulation system.

B. Experimenting aspect

1) While both data analysis and emergence-based observations can be used in the analysis of system performance in ATS, emergence-based observation [3,23] plays a more important role. In other words, the macroscopic behavior of systems, which emerges from the interaction between objects, is more specifically observed and analyzed in ATS.
2) By adopting the concept of many-worlds [21,24] in our work, we found that there were no optimal solutions, but rather, only effective solutions for transportation issues.

C. Decision-making aspect

The concepts of parallel systems and of meta-synthesis are deployed in order to study the issues of control and management of traffic in ATS.

D. Computing aspect

Advanced computing techniques such as P2P computing, grid computing, concurrent computation, etc. are used in ATS to study issues particular to large traffic networks which require a lot of computational effort.

IV. CONCLUSIONS

In this paper, the concepts and methods of artificial transportation systems (ATS) were explored from the perspective of complex systems. The effectiveness of agent-based modeling and the principle of simple objects and relationships in ATS were also examined from the perspective of complex adaptive systems. Essential differences between ATS and traditional traffic simulation systems were proposed.

Our future work on ATS theory will include how to deploy emergence-based observations on the ATS platform and how to rationally apply the concept of many-worlds to ATS.

ACKNOWLEDGMENT

Thanks to Xiqin Wang (Department of Electronic Engineering, Tsinghua University) and Qinghai Miao, Fenghua Zhu, Yanchuan Liu, and Yan Ou (Lab of Complex Adaptive Systems for Transportation, Institute of Automation, Chinese Academy of Sciences) for their invaluable discussions and support for this article.

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