Toward a Revolution in Transportation Operations: AI for Complex Systems

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Increased traffic congestion and the associated pollution are forcing everyone in transportation to think about rapid changes in traffic processes and procedures to keep our mobility safe, comfortable, and economical. IT-driven intelligent transportation systems (ITSs) have recently emerged to meet this challenge. Many people see this emergence as part of normal evolutionary adaptation to new traffic conditions and technology. They consider current ITS applications perfectly adequate to the times and a safer, wiser response to today's and tomorrow's transportation problems.[1,2]

However, technological changes and theoretical developments have created opportunities for fundamental restructuring of transportation management that could lead to significantly expanded capacity and improved efficiency. Recently, Chinese AI researchers have been working on ways to transform systems and methods along this direction.

This research centers on the ACP (artificial, computational, parallel) approach. This approach involves modeling with artificial systems, analysis with computational experiments, and operation through parallel execution for control and management of complex systems with social and behavioral dimensions.[3–6] Transportation systems are typical examples of such complex systems. In many aspects, this approach is driven by new developments in agent technology, computing architectures, and networked operational environments. It's also motivated by the desire to develop, organize, and apply AI methods and techniques for complex systems according to the decision-making structures and procedures in cybernetics and modern control theory.

ACP and Complex Systems

Figure 1 presents an ACP-based framework for the control and management of complex systems. This framework is a generalization of the feedback control mechanism in control theory, where researchers have developed solid, effective mathematical methods and analytical tools for modeling, analysis, and synthesis. For complex systems and the corresponding decision problems, however, we must take into account social and behavioral dimensions beyond traditional mathematical analysis. AI techniques can play a critical role in this process, especially in the construction of agent-based artificial systems and in issues related to social computing, behavioral modeling and prediction, and intelligent decision-support systems.

In the ACP framework, the actual system and its artificial counterparts can be connected in various modes for different purposes. By comparing and analyzing real and simulated behaviors, we can learn and predict systems' future actions and accordingly plan and modify control and management strategies for their operations. Let's look at three typical connection and operational modes.

Learning and Training

In this mode, the actual and artificial systems are loosely connected, and high fidelity between the two usually isn't required. The artificial systems serve mainly as a data center for learning operational procedures and for training operators and administrators. Primitive examples of this mode are operator training systems and dispatcher training systems for petrochemical production and power grid management. In many applications, the artificial systems can serve as backups to support actual operations in emergencies.

Experimentation and Evaluation

Here, artificial systems serve mainly as a platform for conducting computational experiments or for systematic, continuous application of computer simulation programs to analyze and predict behaviors of actual systems in different situations. In addition, we can use this mode to estimate, evaluate, and validate the performance of proposed solutions for online and offline decision making.

Control and Management

In this mode, the actual and artificial systems must be connected in real time and online, and the artificial systems must replicate actual behaviors with high fidelity. In this case, we can use the behavioral differences between the two types of systems to identify operational parameters and generate feedback control. We can also use this mode to support various optimization strategies for performance improvement, particularly rolling-horizon optimization techniques.

The last mode is a generalization of adaptive control methods developed in control theory, where AI-based artificial systems replace the analytic reference models. So, the proposed parallel execution provides an effective mechanism to apply well-established algorithms in adap-

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tive and intelligent control theory for operational management of complex systems.

TransWorld

Urban transportation systems are typical complex systems with both engineering and social components, thus providing an ideal case study for testing the ACP approach's usefulness and effectiveness. To this end, we need to establish various artificial transportation systems (ATSs) to model and analyze traffic problems. Another goal of ATSs is to create a dynamic or "living" ontology to represent and organize transportation knowledge, such as methods, algorithms, regulations, and case studies, in a way that's effective for search and ready for computing and implementation.

TransWorld, a computer program based on social and behavioral modeling for ATSs, is under development at the CAST (Complex Adaptive Systems for Transportation) Lab at the Chinese Academy of Sciences Institute of Automation. Figure 2 illustrates the TransWorld system architecture.

TransWorld differs from other computer traffic simulation programs in three main aspects. First, similarly to computer games, it can generate artificial traffic behaviors and other related data using only population statistics and behavioral models. This is useful for testing and validation in many transportation applications, especially at the level of logical correctness.

Second, it provides a hierarchical environment for integrating and exchanging information for traffic modeling and analysis at different resolution levels, from microscopic, to mesoscopic, to macroscopic emulations.

Third, it offers a platform or a "living traffic lab" for computational experiments for transportation analysis and synthesis.

TransWorld is based on agent programming and object-oriented techniques for social and behavioral modeling. Recipes and architectures developed for conventional traffic simulations, especially those developed for Transims, DynaSmart, and DynaMIT, are also useful for the construction of TransWorld.

To promote the concept and application of ATSs, the IEEE Intelligent Transportation Systems Society established in 2004 its Technical Committee on ATS and Simulation and a corresponding international workshop. At the 2008 IEEE Workshop on ATS and Simulation, a proposal was made to set up standards and procedures for constructing model transportation systems (MTSs) using an open-source version of TransWorld. The purpose is to establish an open protocol and platform so that transportation researchers and practitioners worldwide can collaborate to develop MTSs at different scales for testing, evaluation, and validation. MTSs can also serve as toolkits or repositories for reusing recipes and architectures in transportation studies. Unlike conventional traffic simulation programs, those MTSs would run continuously (just like real traffic systems in real cities) on the Internet through Web computing. Like model economic systems, MTS offers an effective tool for conducting research and evaluating performance related to real-world transportation problems.

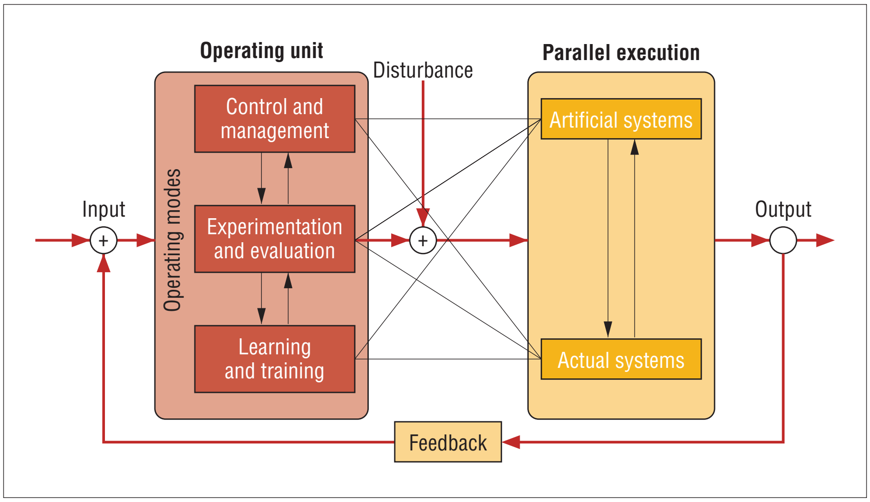

Figure 1. The ACP (artificial, computational, parallel) framework for the control and management of complex systems. The motivation is to develop and organize AI methods and technology according to the structure of modeling, analysis, feedback, and management.

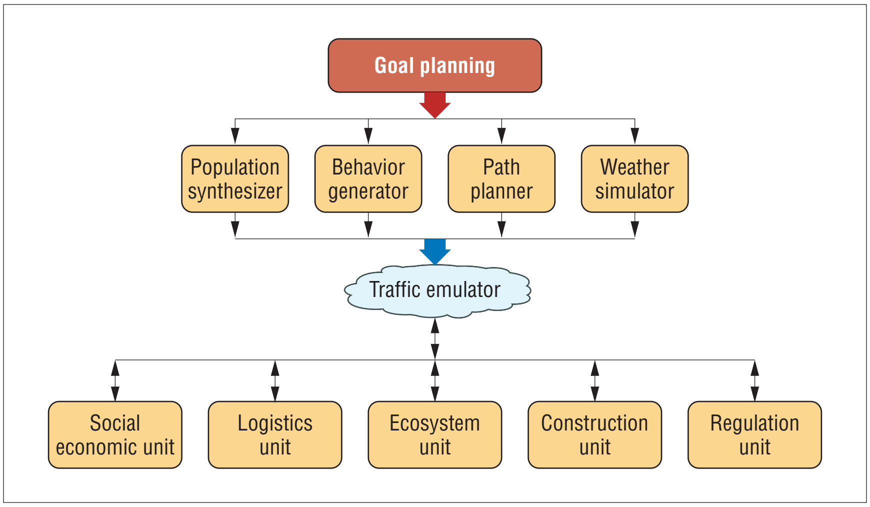

Figure 2. The TransWorld program for modeling artificial transportation systems. In addition to the functionality of conventional traffic simulations, TransWorld's objective is to generate traffic data for testing and evaluation based on social-behavioral modeling and population information.

Parallel Traffic Management Systems

Once ATSs are available, a parallel traffic management system (PtMS) can be established according to the ACP framework (see Figure 3 on the next page). A PtMS can include multiple ATSs for parallel management. For example, we can create different

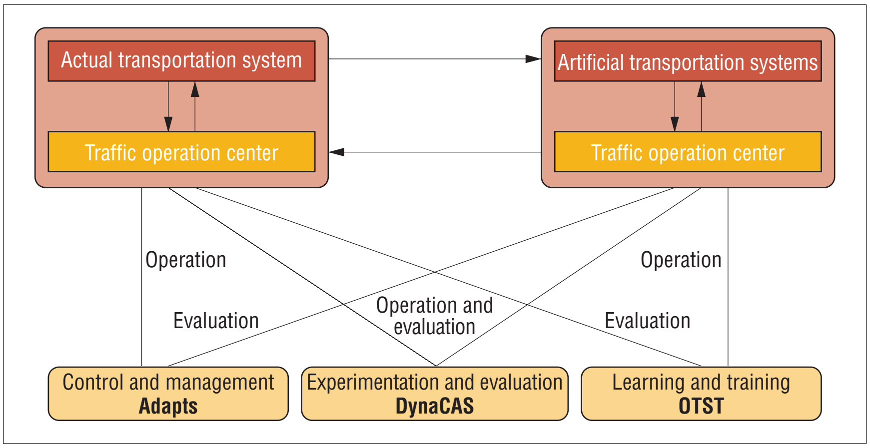

Figure 3. Parallel-traffic-management-system architecture and operation. Artificial transportation systems become an integrated and continuous operation of actual traffic management centers.

ATSs to investigate historical traffic situations, normal and average performance, optimal and ideal operations, or worst-case scenarios for disasters and emergency management. Through the parallel operations of the actual transportation system and its corresponding ATS, we can evaluate the effectiveness of different traffic strategies under various conditions and expectations. This approach will also let us obtain and combine useful information to make decisions that will improve performance.

In a PtMS, both actual and artificial traffic systems can be operated by identical but independent TOCs (traffic operation centers). Also, transportation operations are carried out under the three modes as discussed previously.

In the learning-and-training mode, OTSTs (Operator Training Systems for Transportation) handle operations for traffic operators and administrators. An OTST should incorporate actual procedures for traffic operations and emergency handling to make its functionality more realistic and effective. OTST sessions can be generated manually by human operators or automatically by agent programs. Through agent-based behavioral modeling, automatic sessions can conduct accelerated testing and evaluation of the reliability and effectiveness of traffic operational procedures and regulations.

In the experimentation and evaluation mode, the DynaCAS (Dynamic Network Assignment Based on Complex Adaptive Systems) system conducts computational transportation experiments, detects existing and emerging traffic patterns, and supports the operation of both Advanced Traveler Information Systems (ATISs) and Advanced Traffic Management Systems (ATMSs). Its main functionality includes estimation and predication of traffic network conditions, performance testing and evaluation of different traffic control and management measures and information dissemination strategies, and decision support for traffic operators and individual drivers. For more detailed information on DynaCAS, see the article on page 19 in this issue.[7]

In the control and management mode, the Adapts (Agent-Based Distributed and Adaptive Platform for Transportation Systems) system provides environments for designing, constructing, managing, and maintaining autonomous-agent programs for traffic tasks and functions. Those agents are delivered to traffic control centers, roadside controllers, sensing devices, and information systems via communication networks to make correct decisions and collect the correct information at the correct times. The CAST (Complex Adaptive Systems for Transportation) Lab has designed and manufactured special intersection light controllers that can host traffic control agents.

One specific implementation of a PtMS is the CAST architecture. Figures 4 through 6 show CAST's software architecture, hardware system, and field-testing facility in Jinan, Shandong, China. CAST is in the evaluation and testing stage; a full field implementation at a TOC is expected soon.

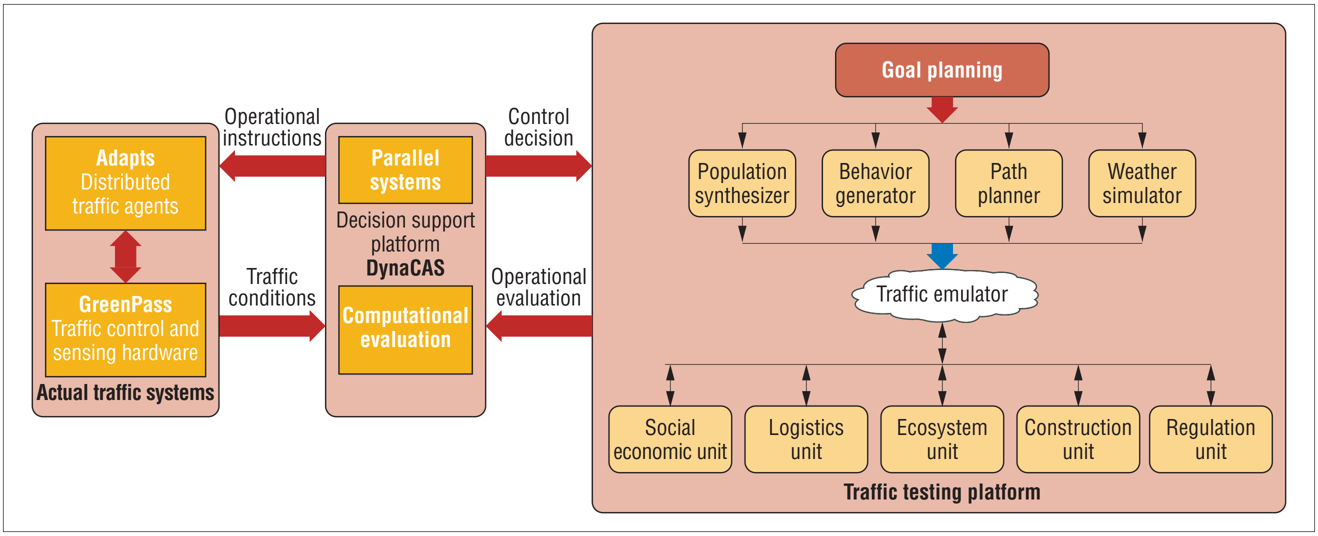

Figure 4. The CAST (Complex Adaptive Systems for Transportation) software architecture. GreenPass resides in local traffic controllers, while Adapts, DynaCAS, and TransWorld run at remote traffic control and management centers.

The ACP approach represents a breakaway from existing methods for control and management of complex systems. (For a look at ACP approaches for areas other than transportation, see the sidebar on the next page.) Its underlying assumption is that the human capacity for modeling, analyzing, and predicting in complex systems is fundamentally limited. In many cases, what we're trying to do is to predict the unpredictable. The contradiction can be solved only along some new dimensions of thinking. In the ACP approach, this new dimension is possibility instead of determinism or probability, as in current analytic reasoning. In other words, we emphasize the psychological effects in dealing with complex systems, and the ACP approach provides a computational platform for realizing this emphasis.

The ACP framework can incorporate many existing techniques. Particularly, this framework enables

Figure 5. The CAST hardware system demonstrated at the 11th International IEEE Conference on Intelligent Transportation Systems (ITSC 08). The CAST traffic controllers support remote agent programming and operation, as well as hardware-in-the-loop computer simulation.

Figure 6. Agent-based control and camera-based sensing devices for field-testing CAST. To minimize interruption to traffic operations, CAST field evaluation extensively uses wireless communication and cameras.

Other Complex Systems

With support from Chinese research agencies and industries, researchers have applied the ACP (artificial, computational, parallel) approach to the control and management of complex systems for fields such as energy production, petrochemical processes, agriculture, ecosystems, and socioeconomic studies. Here is a brief description of several ACP-related projects.

The National Natural Science Foundation of China recently initiated a key project to establish a computational platform to support research related to the complexity, security, and efficiency of e-commerce systems.[1] The project's main objective is to construct model e-commerce systems using techniques in artificial societies to

- emulate transaction processes and buying-selling behaviors,
- conduct computational experiments for benefit analysis and performance evaluation, and
- support reliable, effective e-commerce operations.

The project is also applying the ACP approach to develop a dynamic, "super" ontology to integrate and organize e-commerce knowledge in a searchable, computable fashion.

The PeMS (Parallel Emergency Management Systems) project involves a platform for testing, evaluating, and validating the reliability and effectiveness of various emergency measures and procedures, and for supporting real-time execution of emergency operations.[2] PeMS uses game engine techniques to create scenarios to emulate social events and human behaviors in disaster situations. The National Natural Science Foundation of China will launch a major project in this area early next year.

The P2GS (Parallel Power Grid Systems) project deals with management of complex power grids.[3] Supported by Southern Power Systems of China, this project has applied the ACP approach to establish an artificial power-grid-network system to emulate social and behavioral aspects of the complex power supply network covering the five regions in southern China. The hierarchical representation of model networks enables computational experiments to test and evaluate planning, scheduling, operational, and emergency-handling schemes for managing the real power grid system. The project uses parallel execution for online decision support, rolling-horizon optimal scheduling, and real-time response for emergency management in regional power-network-management centers.

The PyMS (Parallel Ethylene Management Systems) project, funded by the Maoming Petrochemical Works, involves control and management of a large-scale ethylene plant (60,000 to 1,000,000 tons per year).[4] Unlike traditional process control and management systems, it includes social and behavioral dimensions of operators and managers when evaluating the reliability and efficiency of production and safety regulations. Figure A shows the PyMS structure and process.

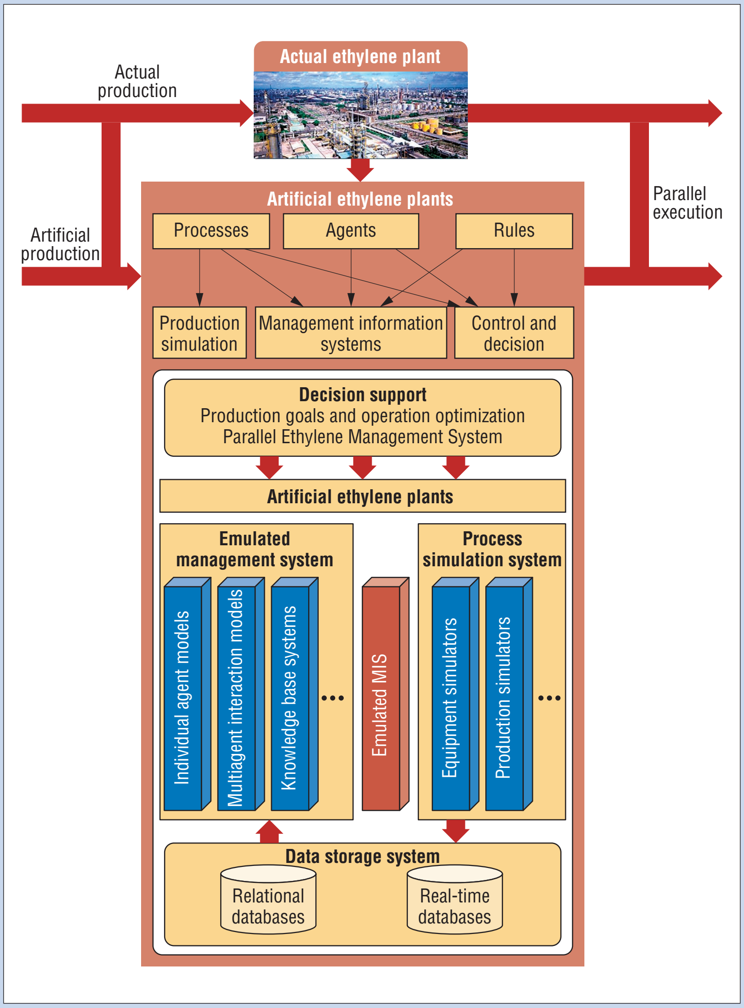

Figure A. The ACP approach for production management of ethylene plants. Computational experiments enable quantitative evaluation of the effectiveness and reliability of plant management and safety procedures and provide real-time decision support for production.

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- scientific applications of game techniques;
- continuous, systematic utilization of simulation techniques during the whole life cycle of complex systems, instead of limited applications during design and preconstruction; and
- computational experiments that employ statistical analysis and pattern discovery to investigate the future of complex systems, instead of purely statistical approaches based on historical data and past experiences.

Clearly, AI methods and computational-intelligence algorithms will be critical to the ACP approach's success in solving the real-world problems of complex systems.

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