A Survey of Emergent Behavior and Its Impacts in Agent-based Systems

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Abstract - **Increasingly, software agents are evolving from the roles of facilitators into decision-makers in managing complex, real-time systems such as logistics enterprise. Emergent behavior is that which is not attributed to any individual (agent), but is a global outcome of individual (agent) coordination. While agent's degree of autonomy and responsibility will continue to increase with time, the impact of emergent behavior in agent system on the performance and stability of these systems become an important issue. We found that emergent behavior is a major concern of potential users while we try to apply agent technology to such industry areas as transportation planning and logistics coordination. To really make agent technology work in industry convincingly, it is valuable to do a study of emergent behaviour and its impacts to the application of agent technology. This paper reviews the research on emergent behaviour, discuss its research challenge and application impact, and suggest research directions on agent emergent behaviour.**

I. INTRODUCTION

Today the Internet is often considered as a thriving environment where billions of software agents find and process information and disseminate it to humans and, increasingly, to other agents. Agents will naturally evolve from facilitators into decision-makers, and their degree of autonomy and responsibility will continue to increase. Transactions among software agents will eventually represent a significant portion of the world communication, transaction and economy.

Agent Technology is a new software paradigm for managing complex, real-time systems such as logistics operation. The benefit over standard software approaches is that agents can be programmed to proactively achieve predefined goals such as coordination of complex multi-dimensional activities in a logistics enterprise. However, to exploit the benefits offered by software agents, it is vital to ensure the agent is properly implemented to leverage all available assets and services so the company can quickly and accurately respond to changes in the business environment.

However, autonomous software agents are not people! They can make decisions and act on them at a vastly greater speed. They are also less sophisticated, less flexible, less able to learn, and most importantly lacking in "common sense". Given these differences, it is possible that software agents can behave in strange and unexpected ways.

This unexpected behavior, often termed as "emergent behavior" is not part of an agent's specification, but usually arises from the outcome of agent coordination. The study of emergent phenomena is at the core of a developing field in the study of complex dynamic systems [6, 7, 10, 20], which seeks to understand how systems of interacting components evolve over time.

Real-time control and coordination is important for effective logistics management at the operational level. However, past studies had shown that emergent behavior of agents is a major concern of potential users. There is a need to study how to identify and handle emergent behavior in agent-based application for logistics domain where different agents make independent decisions based on the interaction with other agents.

This paper investigates on agent emergent behavior and tries to answer the following questions: What is emergent behavior? Is emergent behavior something not part of the system design? What are the possible emergent behaviors of agent-based system? If only complex system has emergent behavior? What are the impacts of emergent behavior, include positive and negative ones? What are the approaches to handle emergent behaviors?

The rest of the paper is organized as follows. Section 2 is about concepts of emergent behavior and related discussions. Section 3 is on agent emergent behavior. Section 4 discusses on how to handle emergent behavior and Section 5 is a summary of the investigation and suggestions on potential directions.

II. EMERGENT BEHAVIOR

A. What is Emergent Behavior

Emergent behavior in software agent is commonly defined as behavior that is not attributed to any individual agent, but is a global outcome of agent coordination. This definition emphasizes that emergent behavior is a collective behavior.

There are also other definitions. "Emergent behavior is that which cannot be predicted through analysis at any level simpler than that of the system as a whole… Emergent behavior, by definition, is what's left after everything else has been explained" [5]. This definition highlights the difficulty in predicting and explaining emergent behavior. If the behavior is predictable and explainable, then it will not be treated as emergent behavior and approaches could be designed to handle the behaviors.

Emergence is also defined as the action of simple rules combining to produce complex results [14]. This definition states that the rules applied to the individuals can be quite simple, but the collective behavior of the group may turn out to be quite complex and unpredictable. Researchers have designed experiment to demonstrate this kind of situation.

While it is true that all behavior comes from individuals, the interactions are what make things difficult to understand. Emergent behavior is essentially any behavior of a system that is not a property of any of the components of that system, and emerges due to interactions among the components of a system.

Borrowing from biological models such as an ant colony, emergent behavior can also be thought of as the production of high level or complex behaviors through the interaction of multiple simple entitles.

Some examples of emergent behaviors:

- Bee colony behavior where the collective harvesting of nectar is optimized through the waggle dance of individual worker bees;
- Flocking of birds cannot be described by the behavior of individual birds;
- Market crashes cannot be explained by "summing up" the behavior of individual investors;
- The success of Extreme Programming depends on the performance of the team exceeding the summed performance of all the programmers.

B. Discussions on Emergent Behavior

Besides the discussions on what is emergent behavior, there are also other discussions on the existence and complexities of emergent behavior. These discussions mostly exist on the web and none exists in the form of books.

For the issue on the existence of emergent behavior, some researchers are of the opinion that emergent behavior exists in many natural and artificial systems. However, there are also researchers who doubt this and argue that sometimes a behavior is wrongly classified as emergent behavior when the real reason maybe just that the designer or the user do not know the rule and principle behind.

For the issue on whether emergent behavior is always complex, some researchers is of the opinion that an emergent behavior need not necessarily be complex, just that it occurs as a surprise to the designer, and it is very difficult to predict a priori what behavior will emerge from a set of interactions. The important thing about emergence is that it forces one to abandon the assumption that complex behaviors must arise from complex rules.

Some researchers argued that interactions are important and complexity is the key for producing emergent behavior. "The interactions are important, but even those, taken in isolation, don't explain emergence. When individuals produce behaviors that affect other individuals and other behaviors, ultimately affecting the original individuals, then you have the complex feedback dynamic you need for emergence. … High complexity is key, because without it we could easily predict the outcomes of these interactions. … and we either fail to expect any result, or expect results that are simple (linear) extrapolations of observed behaviors." (Walden Mathews, C2.com)

C. Research Works

Investigations have been conducted on emergent behavior since 1970s although no big breakthrough till now. Some of the researches are introduced briefly as follows:

- Steven Johnson has conducted research and wrote a book on "Emergence: The Connected Lives of Ants, Brains, Cities, and Software" [17]. What do ants, brains, cities, and software have in common? According to Steven Johnson, they are each "self-organizing" systems, bodies of individual entities whose behavior as individual entities results in a higher level of behavior without a higher level of intelligence to guide that behavior. Evolution, according to Johnson, is the most fundamental example of emergence.
- Kephart et al. [9] conducted research on Emergent Behavior in Information Economies in IBM. The overall goal is to characterize and understand the dynamic behavior of very large open economies of automated information agents. Analysis and simulation of a simple information-filtering economy reveal both efficient self-organization of the brokers into specialized niches and endless price wars, depending on extrinsic costs.
- Works have been done to apply emergent behavior on Game. In [16], Chris Crawford described a game he would like to build, "Attack of Cellular Automata". He was quoted that it might be fun in fighting a war with cellular automata. The cellular automata have emergent behaviors, which gives rise to interesting game-play. A related research was conducted in [15] on creating emergent behavior in cellular game.
- Christie and Fisher conducted research on simulating the emergent behavior of complex software-intensive organizations [1]. Organizations are composed of individuals and groups of individuals who interact with their local neighbors. These individuals and groups inherently have limited horizons both with whom they interact and in what information they can access. Because of this limited

visibility no one individual can "see" the edges of the universe in which they live and in this sense the system can be considered unbounded. A major characteristic of unbounded systems is the fact that global behavior can emerge which cannot be predicted from local actions. These issues have direct relevance to the understanding of software-intensive organizations. However, performing experimental investigations to assess these organizational properties is virtually impossible. They developed a simulation language in which unbounded systems and emergent properties can be simulated and examined.

• Michael J. North et al [11] conducted research on “SMART II: The Spot Market Agent Research Tool Version 2.0” which uses an advanced set of agents and interconnections to represent an electric power generation and transmission system similar to Western’s (a company). SMART II uses a Swarm agent-based framework. The emergent behavior of the agents allows the investigation of market price stability. Agents learn about the cost and value curves of the surrounding agents over time and improve their own behavior to increase their profits.

A number of researchers are working in the agent emergent behavior domain. The followings are the relevant researchers:

• Nong Ya [12] conducted research on “Information Dynamics and Emergent Behavior of Heterogeneous-Agent Systems”. The project presents an effort to establish theories and techniques of modeling, analyzing and controlling information dynamics and emergent behavior of heterogeneous-agent systems and demonstrate the application of these theories and techniques to heterogeneous-agent systems making up information supply networks.

• Peter Wavish [18] conducted research on “Exploiting emergent behavior in multi-agent systems” – (Philips Research Laboratories). His work addresses the question of how to exploit emergent behavior in the design of multi-agent systems. The method advocated is to design the individual agents so that they maintain symbolic representations of emergent behavior which can then be used as a basis for building higher level behaviors.

• Alexander, U. Berezhnoy [2] conducted research on Emergent behavior in Multiagent System (MAS) by designing an experiment to demonstrate emergent behavior in multi-agent system, but no reason are given to the appearing behaviors. During this initial research they created an MAS that is capable of emergent behavior. First they described the essence of the system and show why it can be considered a legitimate MAS. Then they presented the behavior exhibited by the system during the experiments and corroborate why it should be considered emergent.

• Uri Wilensky (in Center for Connected Learning and Computer-Based Modeling of Northwestern University, USA) conducted research on Modeling Nature’s Emergent Patterns with Multi-agent Languages StarLogoT in 2001 [21].

• Dooley, K., and S. Corman ," (Lab of Organization, Arizona State University) conducted research on "Agent-Based, Genetic, And Emergent Computational Models Of Complex Systems” [4]. In their research, emergence is “the arising of new, unexpected structures, patterns, properties, or processes in a self-organizing system. Emergent phenomena seem to have a life of their own with their own rules, laws and possibilities unlike the lower level components.”

There are ongoing discussions and investigations on emergent behavior by various researchers. In-depth research works are needed for exploring the fundamental essence of emergent behavior.

D. Related Tools and Modeling Languages

- **Think Tool**

Emergent behavior is becoming such a powerful technique that researchers at places like the Santa Fe Institute and startup companies like Thinking Tools, Inc. are turning it into a business. Because emergent behavior simulations generate unpredictable scenarios, they are a perfect tool for training strategists and planners.

The software product from Thinking Tools, called Project Challenge, is an agent-based simulation of project management. It employs a video game-like user interface over a simulator that uses techniques like emergent behavior and chaos theory to train managers. Project Challenge subjects its players with true-to-life scenarios ranging from cost overruns, to people-problems and hiring fiascos. These scenarios use sophisticated agent-based techniques to hone project leadership skills.

- **Starlogo and Net Logo**

StarLogoT [21] and NetLogo [22] are modeling language (agent-based or object-based parallel) designed to help learners explore and construct models of complex phenomena. These two languages are descendants of a lineage of StarLogo languages [21] that grew out of the Logo programming language.

StarLogo is a version of the LogoLanguage, developed as a masters thesis project by Mitchell Resnick, now a professor at the MIT MediaLab. The programming language allows users to simulate massively parallel systems, such as Turtles, Termites, and Traffic Jams. It could be used to explore the counterintuitive world of decentralized systems and self- organizing phenomena.

III. AGENT EMERGENT BEHAVIOR

A. Rationale for Multi-agent Systems

Multi-agent systems are systems composed of agents coordinated through their relationships with one another. An MAS is a collection of intelligent software agents that coordinate to achieve certain goals. Some of the rationales for multi-agent systems are as follows:

• A single agent could be constructed that does everything, but such heavy-weight agent represents a bottleneck in speed, reliability and maintainability. Dividing functionality among many light-weight agents provides modularity, flexibility and extensibility.

• Specialized knowledge is not often available from a single agent (i.e., no omniscient agents). Knowledge that is spread over various sources (agents) can be integrated for a more complete view when needed.

• Applications requiring distributed computing are better supported by MAS. In this context, agents can be designed as fine-grained autonomous components that act in parallel. Concurrent processing and problem solving can provide solution to many problems that are usually handled in a more linear manner.

• To support multi-agent systems, an appropriate environment needs to be established. MAS environments provide an infrastructure specifying communication and interaction protocols, and are typically open and have no centralized designer or top-down control function.

B. Emergent Behavior in Multi-agent System

One of the most interesting aspects of MAS is emergent behavior. In this section, we explore emergent behavior in MAS to try to find the ways in which it can be initiated and controlled. We will also discuss if emergent behavior has useful implications in Artificial Intelligence (AI) research that is aimed at the modeling of natural intelligence.

The term "emergent behavior" in the context of this section refers to the behavior of a multi-agent system that is not attributed to any individual agent, but is a global result of coordination between multiple agents. Note that no individual agent has a capability of exhibiting such behavior; it can only occur as a "joint effort." Most emergent behavior can be deduced from the set of actions that agents are able to perform. However, in scenarios where agents have a wide range of available functionalities and where the interaction and coordination among them is flexible, emergent behavior cannot always be predicted with high certainty. Thus, what good is emergent behavior that is unpredictable and what can it be used for?

The primary goal of AI is to artificially create intelligence equivalent to human. One of the main ways of achieving artificial intelligence is by closely modeling after the natural one. Since human intelligence is mainly a product of the brain and the environment in which it resides, our intelligence can also be seen as an emergent behavior of our brain cells. In fact, they can be regarded as systems of coordinating cells. There are many different kinds of cells, all with their own tiny tasks and goals, yet the outcome of their interaction and organization is strikingly amazing. Cells can be viewed as complex interactions of the molecules that make them up. The molecules are in turn made up by coordinating atoms, and atoms can also be broken down into different elementary particles. At the lowest level of view, it is precisely these elementary particles that comprise everything, including humans. It is then possible to create a software simulation of the cells and their environment so that their interaction would result in the formation of more complex entities such as a human being? These ideas are the main motivating factors in studying the unpredictability of emergent behavior and its potential implication to the study of AI.

C. Achieving Emergent Behavior in Multi-agent System

In order to study emergent behavior in a multi-agent system, it would be necessary to first verify that it is possible to achieve such behavior. Given a simple, but fully functional multiagent system and the environment in which it situates, the interaction among the agents should result in an emergent behavior of the system. An example of a fully functional multiagent system is demonstrated by the Multiagent Systems researchers at Carnegie Mellon [18]. The criteria used to define a fully functional multi-agent system are as follows:

• each agent has incomplete information or capabilities for solving the problem and, thus, has a limited viewpoint;

• there is no system global control;

• data are decentralized;

• computation is asynchronous.

Based on the principles above, we intend to design a multi-agent system and use this system in a set of experiment to demonstrate and explain emergent behavior, especially in logistics planning and scheduling.

IV. 4. MANAGING EMERGING BEHAVIOR

Some researchers suggested that emergent behaviors are difficult to control. Based on their reasoning, emergent behaviors are what the designer and the user do not desire as they do not understand the rule or the principle behind these behaviors. They do not know the WHY and WHAT about the emergent behaviors of the systems they involved. If they know what the behaviors are and the reasons for the behaviors, then they should know how to control, make use of or avoid the emergent behavior.

However, because of the risk and cost of emergent behavior, researcher still carried out study on how to control emergent behavior. Parunak, and VanderBok [8] studied the management of emergent behavior in distributed control systems. Their study showed that a population of asynchronously executing processes without central top-down control can exhibit unexpected or "emergent" behavior at the system level. To the plant engineer, this behavior may look like noise or error conditions, but it is generated by deterministic interactions among control elements, not random events or unit malfunctions, and it must be managed accordingly. They illustrated the potential for this kind of behavior among welding robots in an automotive body shop and showed how research in nonlinear systems theory and agent-based control can be used to detect and manage such interactions. They also identified some requirements that these agent techniques place on emerging standards for data and control models.

This study showed that when emergent behavior is responsible for undesirable behavior, several strategies can control it.

• eliminate the nonlinearity in the system that generates this behavior;

• lock all the details of the plant's operation under a centralized control algorithm;

• damp out any variation in the system by limiting performance well below the optimal level;

• use of distributed computational control elements.

More complicated schemes of inter-agent coordination include bidding protocols, in which each controller bids for access to a scarce resource (such as the power mains). Each controller is assigned a budget of funny money periodically, and bids for one of the available slots. The amount it bids is calculated based on how wide a window the controller has in which to complete the weld. Slots are awarded to the highest bidders. As one controller's budget is depleted, it must wait its turn, so that other controllers that were unable to get a slot earlier have a chance to get one later. This kind of synthetic economy has been used to manage the climate control system in an industrial research facility, and outperforms a conventional system that had been hand-tuned over a two-year period by professional facilities engineers [3].

As these examples make clear, agent-based control schemes require careful tuning to ensure that they alleviate the undesirable emergent behavior and do not cause other problems of their own. Agent-based simulation is again an indispensable tool for tuning and testing these algorithms before they are applied to actual facilities.

V. Summary and Suggestions on Potential Directions

As discussed previously, the study on emergent behavior is still in its infant stage. Different researchers have different viewpoints to the concepts of emergent behavior. To the best of our knowledge, currently there are no academic books that focus particularly on emergent behavior. Also, there are few real application systems on controlling or applying of emergent behavior.

Due to the limited research work carried out in this area, the study on emergent behavior would require lots of effort on pure research and the end result may have not much application value in the near future. However, some suggestions for the study on emergent behavior of agent-based system are given below.

First, analysis and simulation can be used to study the collective behavior of models of large populations of software agents employing a variety of interaction patterns and adaptive utility-maximization algorithms.

Second, if the vision of an agent-based logistics system is to be realized, then it must be demonstrated that, within their domain of application, agents can attain a level of performance that rivals or exceeds that of humans on average, without introducing undue risk. Otherwise, people would not entrust agents with making decisions. One aim in our work is to provide such a demonstration. Through a series of controlled laboratory experiments in which humans and agents participate simultaneously in a realistic case, we hope to show that software agents can consistently obtain greater gains from the operations than their human counterparts.

Third, the system to be studied should be complex enough to show emergent behavior, and the logic of the system should be simple enough to demo emergent behavior. Various domains ranging from colonies of insects to energy exchange in cell mitochondria could be considered. Study could also be carried out on models dealing with shop-bots and their likely impact on markets, information bundling by software agents, and multi-agent learning etc. To us, research effort would be concentrated on modeling of logistics coordination, such as ammunition storing, inventory control in a network, and vehicle routing. In particular, we can focus on issues of logistics efficiency, spontaneous niche specialization, and response time that may threaten the viability of a logistics system.

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