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Challenges in the Design of Complex Systems

From Automation to Intelligence: Self-organizing Systems

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Abstract

As the world advances in technology today, manufacturing companies are moving from automation to intelligence, with self-organizing systems at the forefront of that development. Self-organizing systems, e.g., swarm robots, have great potential for adapting when performing complex tasks in the ever-changing manufacturing enterprise environment. In 2040, a successful company should be able to design self-organizing systems to accomplish production goals and leverage the system's characteristics to achieve higher efficiency. However, such systems are difficult to design due to the stochasticity of the system performance and the non-linearity between the local actions/interaction and the desired global behavior. In order to address this, in this essay, I define the characteristics of successful companies with self-organizing systems and propose a framework for a class of design methods. This design framework can be used to improve the efficiency of manufacturing companies and can be used as a reference for future designs.

Key Words

Self-organizing Systems, Reinforcement Learning, Surrogate Models, Compromise Decision Support Problem

1. Introduction

As manufacturing companies evolve, they will gradually move toward intelligence, and a self-organizing system that operates excellently should be the ultimate goal of their manufacturing plants. As it stands now, the industry is inspired by self-organizing systems in nature and has developed techniques such as reinforcement learning to make it possible for multi-robot systems to perform complex tasks. A swarm of robots is an example of a self-organizing system. For manufacturing companies, it should be possible to complete manufacturing tasks with multi-robot self-organizing systems in the year 2040. Engineered self-organizing systems consist of a large number of simple individuals and tend to have better flexibility as well as lower manufacturing costs.

Figure 1. some examples of self-organizing systems

As shown in Figure 1, there are many examples of self-organizing systems in nature, such as geese flying in teams, and people learning from nature, such as self-organizing industrial robots in factories, and object distribution robots in smart logistics, driverless cars in smart cities, and so on. From the superiority of these self-organizing systems, we can get some system properties. A self-organizing system does not need the intervention of external forces to establish order, increase the degree of order, and can even change from one organizational state to another on its own. That means it's an intelligent system that doesn't need more people to intervene, and people can do design work at the highest level possible. From a design perspective, designers typically do not impose on the system some external forces to force it in a certain direction but design the self-organizing system itself with some properties to direct it to some good emerging behaviors.

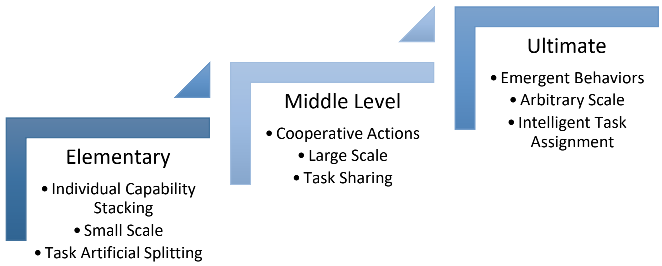

Figure 2. development of self-organizing systems

I foresee a gradual development of self-organizing systems between now and 2040, as in Figure 2. Most of the self-organizing systems that we have in companies now operate independently and autonomously, and then are organized together. They go to small-scale enterprise production by manually assigning different tasks. Gradually they will further develop the system, which can allow the various parts of the system to collaborate, especially the collaboration of movements, to be able to form large-scale cooperation to achieve the function of completing tasks together. This will have substantially improved the performance of the system. However, in the more distant future, I predict that in 2040, self-organizing systems will probably be able to form emergent behaviors, i.e., no longer some prescribed actions, but cooperation to achieve more efficient group behavior. They can freely combine into any size and intelligently assign tasks to achieve a truly intelligent self-organizing system.

Therefore, to ensure the efficient and effective operation of the system, a scientific method to design a self-organizing system is needed. So, in this paper, we answer four questions:

- How do we achieve the expected global behavior by designing the local parameters of robots?
- How do we train the system to be self-organizing?
- How do we relate local parameters to global behavior?
- How do we explore the solution space of the whole system?

To answer the questions, a method to design the multi-robot system is proposed. The rest of this paper is organized as follows. In Section 2, I define the characteristics of a successful manufacturing company in 2040 and introduce the framework to facilitate the company staying competitive. In Section 3, I propose research questions for the design and challenges of self-organizing systems and propose the short answers related to the research questions. In Section 4, I presented the role of the framework, summarized the entire paper, and highlighted future developments.

2. The Characteristics of a Competitive Company with Self-organizing Systems

2.1 Define self-organizing systems in 2040

Self-organization is a self-adjustment process of the system. The whole process is formed by the autonomous interaction of individuals within the system, without centralized control. Each individual is not capable of completing difficult tasks alone, and their capabilities and interactions are very limited, a state where the whole picture is unknown. Nowadays, the global behavior of the system is hard to predict [1]. But by 2040, this is the path that self-organizing systems must take, and companies will be looking at how the system is designed and will design the most appropriate global action. Designing such systems is a challenging task because of the difficulty of defining the micro-macro link [2]. In 2040, companies will study the interaction of robots in the system in-depth and understand how individual parameters affect the system as a whole so that they can design each part of the system and design their interaction in a way that achieves emergent behavior.

I believe that companies will take advantage of the emergent behavior of such a self-organizing system, not only to connect each automated action machine but also to allow them to adjust their own behavioral parameters and interaction, so that they overall reach an optimum. In this way, we can gradually reach the overall intelligence from individual automation.

2.2 Self-organizing system applications in 2040

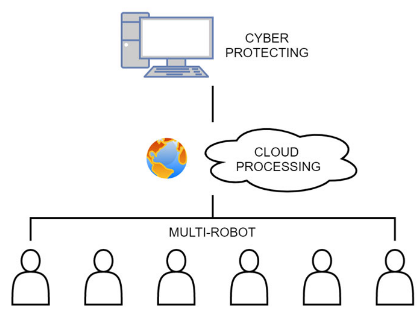

Figure 3. Applications in 2040

Multi-robot control

The reason for the increasing application of self-organizing systems is multi-robot control. The multi-agent systems themselves have been much studied and applied, and we will go deeper and consider them as the most directly demonstrated part of the whole self-organized system as well as the output part of the social system. They can make more use of emergent behavior to directly change the whole system.

Data storage and processing

Cloud-like processing will still be used in 2040, not only as part of a multi-robot system but also to exploit the properties of self-organizing systems in greater depth. I believe that by that time, every cloud processor can also be considered as part of a self-organizing system and can consider this approach of parallel mode computing as a self-organizing system and optimize the computational methods, and data storage methods in it. They will have a deeper computational speed and data fetching speed that is better than the overall specific

Cyber system

Not only that, but we need to take the cyber system into account. Since a self-organizing system is part of a cyber system, it also has certain self-organizing properties within the cyber system. We can also think of the entire network security system as a self-organizing system, except that the "bots" will be similar to intrusion probes. What's more, to think deeper, the whole system actually contains the whole Internet of Things, whose terminals are complex and diverse. The networked control of all objects will be a huge self-organizing system, not only computing and processing, but also mutual information interaction and supervision, making the whole system in an unobstructed and fast state of communication.

2.3 What is a successful company with self-organizing systems?

Low individual requirements

In the future, we naturally want each individual to be a simple individual, no longer an exorbitant multifunctional separate part, but a composition of multiple simple parts that can also achieve the same multiple functions. Each robot or part of a self-organizing system is a relatively independent individual, and each individual has the ability to control and make decisions on its own. In other words, it is not like the unified deployment in most of the current systems, but like a social system, after a certain running-in, a feasible task allocation and cooperation mechanism to achieve larger task objectives is formed. Some of our subjective cooperation mechanisms are not necessarily the most direct and effective way to solve the problem, but need some means to find, and make it can cooperate well.

In a self-organizing system, they should be made up of many cheaper and simpler pieces, trained by a collaborative mechanism, to achieve better results. In future production, enterprises not only need to reduce the cost of each part but also need to find a better way of coordination. Whether the decision is correct or not may affect the real benefit of an enterprise.

Great emergent behaviors

The evaluation of the excellent performance in the future also depends on the goodness of the emergent behavior. Emergent behavior actually refers to the characteristics that emerge spontaneously in a self-organizing system beyond the scope of the robot's individual ability. Although there are many publications in the field of robotics on the various actions of individual robots, the problem of how they interact optimally in the field of swarm robots, in particular, remains to be solved. While the performance of individual robots has been fully exploited, the actions of multiple robots are prone to conflict and do not necessarily achieve a "1+1>2" effect.

We hope that in a self-organizing system, each part of the organization can cooperate with each other to achieve the optimal effect, that is, some emergent behaviors appear. Such emergent behaviors do not simply form a queue, but actually, work together to achieve more goals. In the future, enterprises or other fields can use this extra marginal effect to achieve more production or efficiency.

Excellent ability to design robust systems

In the future, we will naturally need self-organizing systems to perform different tasks, and even some tasks may be in unknown states. While it may be reasonable for a functioning self-organizing system to cooperate with each other when there is some emerging behavior, it may not achieve all of your mission goals. And a self-organizing system may not be as predictable as the one being manipulated, and it takes some way to know how well a self-organizing system works. In particular, when certain tasks have multiple evaluation indicators, self-organizing systems require some new adjustments to achieve the desired goals. This means that we need a way to design self-organizing systems that map from individual parameters to overall behavior.

In the future, companies will definitely need to have a grasp of the entire self-organizing system. It can not only achieve an efficient self-organization system, but also coordinate the goals needed by all parts, make trade-offs, and achieve global optimization.

Part of a cyber-physical-social system

A self-organizing system can also be viewed as a social system, but in the case of a company, this social system consists of multiple executive robots. These robots, just like the real society, can work together to complete a task of the enterprise. This kind of system breaks through the existing physical limitation to some extent and truly achieves the high-tech industrialization, making the company further full of competitive.

In 2040, the system will no longer be a single physical system, but a whole connected by network systems, with the capability of a social system. In particular, there will be stronger execution, better collaboration, and more efficient data processing between them.

2.4 A design framework for self-organizing systems

In order to facilitate a manufacturing company to gain the competencies identified in Section 2.3, I propose a framework for designing self-organizing systems. In 2040, companies should not only look at the design of automation for individual robots but also think more broadly about the coordination of entire robotic systems. In other words, after the robot has reached a certain bottleneck that can complete almost all the tasks efficiently, the system design may become a more important problem, which can have high marginal benefits to improve the profits of enterprises. For an outstanding enterprise, from their production point of view, what they need most is to make a system achieve the goals they need and can be optimized as much as possible within a limited scope.

Research Question 1: How do we achieve the expected global behavior by designing the local parameters of robots?

Hypothesis 1: We need an excellent system design methodology that can meet the design requirements while progressively advancing each capability. I present here a framework for system design based on the major challenges at hand.

In Figure 4 we show the overall framework for designing a self-organizing system. In this framework, we illustrate the process of moving from individual robot elements to machine learning methods to overall system performance, with a design space exploration process consisting of surrogate models and solution space exploration in between.

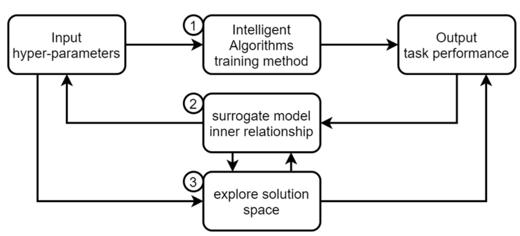

Figure 4. Schematic diagram of the framework

It is necessary to define the individual hyperparameters of the self-organizing system first, and then to know the evaluation index of the task, namely the system output. The whole design process starts with training through appropriate intelligent algorithms, and then the system can achieve some corresponding tasks through training. Then, a surrogate model is used to establish the relationship between local parameters and task evaluation indicators. Using these relations to explore the solution space and find a satisfactory solution, so as to obtain a self-organizing system with good emergent characteristics.

In addition to explaining the composition of the whole system, we need to note that the individual parts within this design framework are the key to developing a self-organizing system.

3. Challenges and Feasible Solutions for Designing the Self-Organizing System

3.1 Effective intelligent control algorithm

For a future-oriented company, the development of the most intelligent algorithms cannot be stopped. Intelligent algorithms should not only be able to be used in production, but also in the design process, but the most important thing is that they must be self-organizing. Only in this way can the superiority of the system be truly satisfied and a higher level of efficiency be achieved.

From a technical point of view, the most feasible intelligent algorithm we have today is the multi-agent reinforcement learning approach. Not only can it have superiority over traditional intelligence algorithms such as genetic algorithms, but it also has great potential for continuous upgrading. Therefore, MARL is an essential part of both the upgrade of the system itself and the basic framework of the system design, and will definitely be useful in the future.

Research Question 2: How do we train the system to be self-organizing?

Hypothesis 2: We use a multi-agent reinforcement learning method to achieve the purpose of self-organization, and the state of local known and global unknown can be realized through multi-agent decentralized, centralized criticism, and robot perception limitation.

As shown in Figure 5, as is typical of a self-organizing system, each agent is executed and then trained based on the overall results. In this way, each agent can learn its behavior and achieve the best overall performance. Each agent learns by its behavior and has a global performance reward. The overall optimization can be achieved through various iterations.

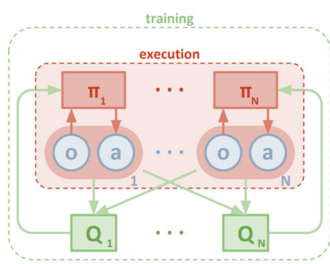

Figure 5. Overview of our multi-agent decentralized actor, centralized critic approach [3]

The principles of reinforcement learning are not repeated here, for details see [3]. We note that an agent can get different reward values through multiple training sessions. The agent achieves the goal like a baby toddler. So, it means that we use multi-agent reinforcement learning as a training tool to allow multi-robot self-organizing systems to achieve the best possible solution for the case of input parameters.

While intelligent algorithms are a great way to train systems, they are still a major challenge today. We do not yet understand the mechanics of it and consider it a black box. By 2040, researchers will have a much deeper insight into it and be able to have more effective ways of self-organization.

3.2 An in-depth analysis of emergent behavior

At present, the emergent behavior of self-organizing systems is not controllable because of the lack of in-depth research on some mechanisms. But in the near future, we're going to go deeper and solve these mysteries. In the future, only when we have a clear understanding of how emergent behavior is generated, we can clearly know how to better plan and design the system to improve business efficiency at a higher level. Nevertheless, we can use the surrogate model to explore emergent behaviors. Only if we understand the changes in emergent behavior through simple models can we go deeper into the reasons for them.

Research Question 3: How do we relate local parameters to global behavior?

Hypothesis 3: We delve into emergent behavior and use agent models to fit the individual-to-whole process.

Self-organization phenomena have been noticed for a long time, especially in the study of ant colonies and related pheromones. For example, Holland proposes that swarm robots use the Stigmergy self-organization of ant colonies to accomplish related tasks [4]. With the increasing maturity of the Internet and various information technologies, the characteristics of information systems have changed greatly, and the scale of the system has become larger and increasing complexity.

The model I envision for 2040 will not be role-playing or hierarchical and pre-organized system, but a more complex one that can interact with each other and adjust based on emergent behavior. The various parts and kinds of robots, like a social system, are organized with each other to run a much larger self-organizing system.

In addition to studying the mechanism of operation of self-organizing systems, we should go for a method of control in unknown situations. Put differently, it is impossible to understand clearly the emergent behavior of all tasks.

I think the surrogate model is a good way to meet all the needs. As the data is acquired through reinforcement learning training, it is difficult to obtain, which greatly affects the amount of data. In addition, the reinforcement learning method itself is not stable. Although the results of the two pieces of training are similar, they cannot be exactly the same. Therefore, we believe that surrogate models such as Box-Behnken designs (BBD) response surface analysis [5] may be very suitable for the mechanistic study and system design of self-organized systems. BBD is a class of rotatable or nearly rotatable second-order designs based on three-level incomplete factorial designs. For three factors its graphical representation is shown in Figure 6.

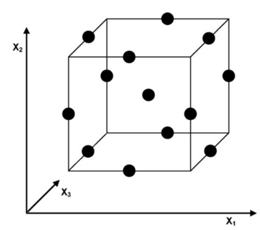

Figure 6. The cube for BBD [4]

By obtaining the required data points, we can naturally fit the corresponding response surface, to get the corresponding relationship. Through the BBD method, we can further analyze various stability conditions of data and compare various fitting results to get a more reasonable way.

We still need to go deeper to understand the whole partial-to-whole process. Like mechanism and surface fitting, we need more effective ways to design self-organizing systems.

3.3 System optimization and adaptation

To make a company to be competitive, which means that the products should meet the needs of customers in many ways, and have as many different aspects of the products as possible. In other words, this means that the system needs to be able to be optimized, and can be tradeoffs based on prior requirements. In the future, a self-organizing system is able to autonomously assign tasks and reach multi-objective optimization.

Research Question 4: How do we explore the solution space of the whole system and meet our needs?
Hypothesis 4: The systems can be explored using multi-objective optimization. For example, we use the compromise decision support problem construct to solve the solution, and then DSIDES and Adaptive Linear Programming algorithm can weigh the solutions under different weights.

For complex systems, each change in a parameter may change the entire system in multiple resultant parameters. So this is not a simple multiplicity of machines controlling one output, but a whole, possibly small change that will have a butterfly effect on the system.

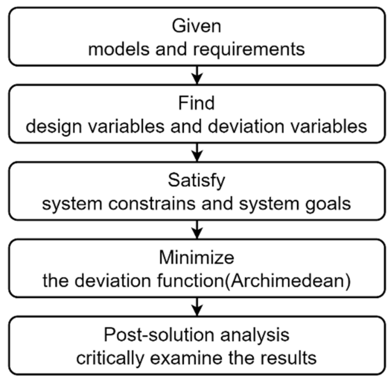

Figure 7. Schematic of the cDSP construct

Compromise Decision Support Problems (cDSP) are used to model engineering decisions involving multiple trade-offs [6]. As shown in Figure 7, we use the cDSP to facilitate designers exploring the solution space and making compromise decisions among multiple objectives in the design of multi-robot self-organizing systems.

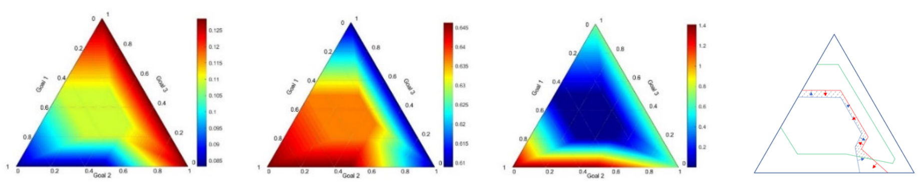

Figure 8. Examples of trade-offs

Based on the mathematical representation of the cDSP structure, we can go ahead and fill in the required parts of the framework to get reasonable design results. Then, as shown in Figure 8, the solution space can be further explored using a tailored computational environment called DSIDES [7] and the Adaptive Linear Programming (ALP) algorithm [8] to find satisfactory design solutions. With different preferences, we could get different results. But the system cannot perform well with all the different goals. Therefore, we need to make some trade-offs in this regard, delimit the corresponding feasible region for the corresponding target value, and then find a reasonable solution within it.

5. Closing Remarks

All in all, self-organizing systems are a promising area of future industry. When we talk about the system of the future, we know that this system is not only a system that can perform tasks automatically, but it should be an intelligent system with self-organization capabilities. Therefore, the design of this type of system will be a major challenge in 2040.

In order to have a head start in the industry, companies must have the ability to develop industrial intelligence. It is necessary to have an in-depth study of the emergent behavior of the system, to update the criteria of the individual, to learn to design the whole system, and to be able to act on a higher level in the whole physical cyber social system.

The challenges they face are not only the development of intelligent algorithms, i.e., the various applications of MARL, but also the mechanistic study of emergent behavior or so-called surrogate models, and furthermore the optimization of the system to cope with the criteria of multiple tasks.

That's why it's a good way to continuously develop the design of self-organizing systems. Not only do we have a deeper understanding of the self-assembling nature of the system, but we can also drive the development of the technology around the system. This means that the framework I have proposed is of great importance, and only by constantly updating its contents will we be able to stay ahead of the curve. Only in this way will companies be able to stand out in 2040 and keep the self-organizing systems they have designed at the forefront of the industry.

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