Engineering 25 (2023) 17–20

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Views & Comments

Structure Analysis of Crowd Intelligence Systems

Yunhe Pan [a,b]

[a] Artificial Intelligence Institute, Zhejiang University, Hangzhou 310027, China
[b] Zhijiang Lab, Hangzhou 310027, China

1. The connotation and characteristics of crowd intelligence

The reason that human beings have evolved to such an advanced level today lies not only in the increase in individual knowledge but also in the structural progress of crowds [1]. Given the importance of the latter, since the late 20th century, researchers have begun to explore management and calculation methods related to crowd intelligence [2], such as the multiagent system, distributed collaboration, and open-source platform.

Since the beginning of this century, with the great development of new information systems [3,4] such as the Internet, big data, and unmanned systems, the potential for crowd intelligence has increased rapidly. With the significant development of smart manufacturing, smart business, smart transportation, digital economy, and smart cities, research on the mechanisms and algorithms of crowd intelligence has become an important new demand. Wu et al. [5] pointed out that crowd intelligence will become a new direction in the future development of artificial intelligence (AI) in China. The participation of a large number of intelligent individuals through the internet framework may result in extraordinary wisdom and abilities, providing a new way to solve open and complex problems. Therefore, Pan [6] took research on crowd intelligence as one of the major development directions of AI 2.0.

The intelligent crowd in crowd intelligence refers to a group of intelligent individuals who work independently toward clear goals on the same platform. The intelligent individual is an autonomous intelligent system, that is, either a human or an information system. Crowd intelligence [2] is a research subject that studies the system characteristics, operation mechanisms, and application technologies of intelligent crowds. Crowd intelligence systems have the following general characteristics:

(1) **Intelligent individuals.** Each individual can perceive the changes in the surrounding environment and adapt to them, such as intelligent and independent cognition, learning, decision-making, interaction, and so on.

(2) **Shared platform.** The crowd of intelligent individuals strives to achieve a certain goal on the same platform, such as a certain field or space.

(3) **Common rules for individuals to follow.** Rules are the constraints and codes of conduct for each individual on the platform. Although all of the contradictions in group behavior cannot be easily removed, successful rules must be able to reduce foreseeable important contradictions that may cause obstacles to achieving the goals.

(4) **Openness.** The number of individuals in a crowd can increase or decrease at any time, for example, they are allowed to register an account and cancel it at any time.

(5) **Common knowledge.** Intelligent crowds share some common knowledge in the common knowledge base. The common knowledge may evolve. The level of common knowledge reflects the level of the crowds.

(6) **Automatic evolution.** Intelligent crowds will evolve automatically over time, which is the result of the integrated evolution of intelligent individuals and the structural relationship of the crowds.

According to several kinds of characteristics of the organizational structure, crowd intelligence systems can be categorized as follows. First, crowd intelligence systems can be divided into single-type crowd intelligence systems and multitype crowd intelligence systems according to the number of types of intelligent individuals in the organization. For example, the latter may include two-type crowd intelligence systems, three-type crowd intelligence systems, and so on. Second, they can be classified according to the relationship between different types of intelligent individuals in the system, such as double-layer crowd intelligence and cyclic crowd intelligence. The incentive and evolution mechanisms of crowd intelligence systems will change with different types and relationships, which will be discussed in the latter parts of this paper.

2. Single-type crowd intelligence and single-level crowd intelligence systems

Single-type crowd intelligence systems refer to intelligent crowds made up of only one type of intelligent individual who perform tasks autonomously. Intelligent individuals in the crowd act, communicate, and coordinate with each other according to the rules, their knowledge and perception of the surrounding environment to complete their own goals and tasks.

The basic structure of single-type crowd intelligence is shown in Fig. 1. Now, we take drivers on the road as an example to analyze the operation of single-type crowd intelligence.

https://doi.org/10.1016/j.eng.2021.08.016

Example 1: Drivers on the road form a single-type crowd intelligence system made up of drivers who obey traffic rules, take the road as a platform, and control the direction, speed, signals, and so on, according to their perception of the environment to reach the destination, as shown in Fig. 2.

The weakness of single-type crowd intelligence systems lies in the contradiction between the local constraints on individuals' perception, communication, and control and the whole influence of their behaviors and decisions. In this case, the contradiction can cause traffic congestion at roadblocks and forks. As shown in Fig. 3, the reasons and solutions for the congestion caused by single-type intelligent crowds crossing roadblocks are as follows:

(1) **The factors that affect drivers' behavior.** These factors include the target direction of the vehicle and the vehicle's perceptions of the environment, including the road, other vehicles, and signs; the traffic rules on the road; the driver's driving experience; and response to changes such as interest, confusion, panic, and so on.

(2) **Analysis of the conditions when there is a roadblock but no traffic congestion.** In Fig. 3, a two-lane road exists in road 1. Before the roadblock occurs, the traffic flow moves at a constant speed s_1. When the roadblock occurs in road 2, the two-lane road becomes a single-lane road, and the speed becomes s_2. Generally, suppose ① the number of available lanes on the road is W, ② the distribution density of moving vehicles in each lane is N km^{-1}, ③ the constant vehicle speed on each lane is s $km{\cdot}min^{-1}$, ④ the traffic density in each lane is $D = s{\cdot}N$ vehicles per minute, and ⑤ the traffic rules have given the minimum safe distance between vehicles at a speed of s, with which we can calculate the maximum distribution density of moving vehicles, N_{max}.

To ensure smooth traffic flow with a roadblock,

$$D_2 \cdot W_2 = D_1 \cdot W_1 \tag{1}$$

where D_1 and D_2 represent the traffic density in each lane in roads 1 and 2, respectively. W_1 and W_2 refer to the number of available lanes in roads 1 and 2, respectively.

$$s_2 \cdot N_2 \cdot W_2 = s_1 \cdot N_1 \cdot W_1 \tag{2}$$

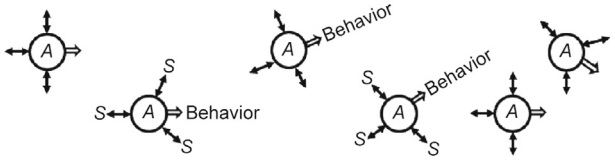

Fig. 1. The basic structure of single-type crowd intelligence. *A* represents an intelligent individual, *S* represents the perception of the environment, and the thick arrow represents direction of *A*'s behavior.

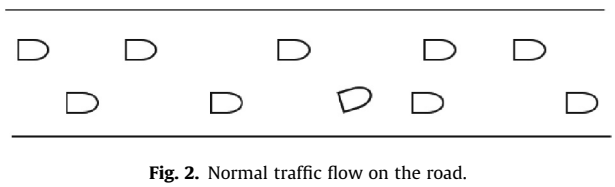

Fig. 2. Normal traffic flow on the road.

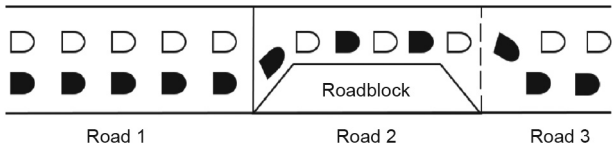

Fig. 3. Traffic flow with a roadblock. Road 1: a two-lane road exists; road 2: the two-lane road becomes a single-lane road when the roadblock occurs; road 3: a two-lane road come back when bypassing the roadblock.

where N_1 and N_2 refer to the distribution density of moving vehicles in roads 1 and 2, respectively.

In road 2 with roadblocks, $W_2 < W_1$ ($W_2/W_1 = 0.5$ in Fig. 3). To keep the traffic flow as smooth as usual, we should make $s_2{\cdot}N_2 > s_1{\cdot}N_1$, such as increasing the distribution density N_2 or speed s_2 of vehicles. If the distribution density in road 1 is close to N_{max}, we should make $s_2 > s_1$. When the two-lane road narrows to a single-lane road, we should make $s_2 \geq 2 \times s_1$. However, it is very difficult for drivers to speed up significantly when merging into traffic and bypassing roadblocks.

(3) **Limitations of single-level crowd intelligence systems.** At the point where the two-lane road 1 changes into the single-lane road 2, drivers will reduce speed due to the unordered interaction and unfamiliarity with the environment. When bypassing the roadblock in road 2, drivers will slow down due to distraction. A common method is to send traffic police officers to direct traffic to merge in an orderly way at the place where the number of lanes suddenly decreases. Then, there are intelligent individuals performing two types of tasks on the road: drivers and police officers. The crowd intelligence system changes from a single-type system to a two-type system. Unable to obtain all of the information, traffic police officers can keep the merging place in order but cannot address traffic congestion caused by vehicles slowing down or merging into the traffic in road 1. At this time, only with all of the information can we make the best coordination. Since each type of intelligent individual only has partial information and belongs to the same level in the crowd intelligence system, it is called the single-level crowd intelligence system. The analysis in this subsection shows that the limitation of the single-level crowd intelligence system lies in failing to master all of the information.

3. The structure of double-layer crowd intelligence systems

Double-layer crowd intelligence systems provide more efficient coordination. They contain two types of intelligent crowds responsible for achieving the targets and making overall coordination. The multitype crowd intelligence system with overall coordination and targeted action is called double-layer crowd intelligence because of the superior-and-subordinate relationship between the coordinator and executor. A general model is shown in Fig. 4.

Because the overall coordinator has all of the information, double-layer crowd intelligence systems show advantages in handling emergencies. A vehicle–road network is an example of

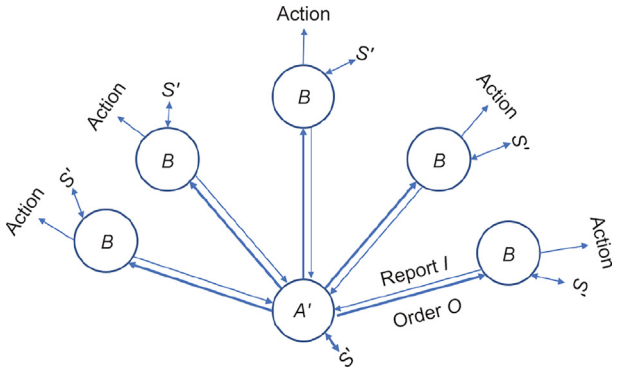

Fig. 4. The basic structure of a double-layer crowd intelligence system with an overall coordinator. *A′* is the overall coordinator which is able to grasp the overall situation and make deployments under special circumstances. *B* is the target executor. The target executors can communicate, share information, and coordinate actions with each other. Under normal circumstances, *B* executes the target autonomously; under special circumstances, it executes instructions of *A′*; *I*: information flow of reports from *B* to *A′*; *O*: information flow of dispatchment from *A′* to *B*; *S′*: information flow of perception and communication.

double-layer crowd intelligence. When vehicles pass the roadblock, as shown in Fig. 3, the intelligent road plays the role of an overall dispatcher. The automatic driving instructions given by the vehicle–road network can not only ensure orderly merging into the traffic at the junction of roads 1 and 2, but also can double the vehicle speed.

The above analysis also points out that in an intelligent transportation system, only by developing a double-layer crowd intelligence system with intelligent autonomous vehicles and a vehicle–road network can the problem of traffic congestion be solved effectively.

Double-layer intelligence can be used in many fields, such as unmanned workshops with flexible coordination, open knowledge base construction systems, and unmanned aerial vehicle fleets with concerted action. The dispatching mechanism varies in different fields.

Example 2: Knowledge absorptive double-layer crowd intelligence is a system that organizes intelligent crowds to provide knowledge for the automatic building of knowledge bases. Its structure is shown in Fig. 5.

In the field of big data intelligence [6], the core technology to solve many problems lies in the construction of knowledge bases. For example, knowledge absorptive double-layer crowd intelligence can be used for federated learning, construction of a knowledge dictionary, and construction and optimization of supply networks, marketing networks, and innovation networks.

According to different tasks and the division of labor, the manager of the knowledge base A'' that masters all of the information in the double-layer crowd intelligence system can choose different dispatching strategies. If A'' plays a strong role, the structure falls into the "plan execution type," and A$''$ is the focus of decision making and dispatchment; if A'' plays a weak role, the structure falls into the "collaborative action type," and the knowledge provider B'' becomes the focus of decision making and dispatchment. At this time, the importance of the information flow of communication and perception S'' and the calculation intensity of autonomous decision making by B'' will increase.

Michelucci and Dickinson [7] pointed out that when combining crowd intelligence with machine performance to solve problems brought by rapid growth, crowd intelligence computing can be divided into three types according to difficulty level: crowdsourcing used to realize task allocation, complex workflows, and the most complex problem-solving ecosystems that address problems through collaboration. In the three types of scheduling calculations, A'' plays strong, medium, and weak roles, respectively.

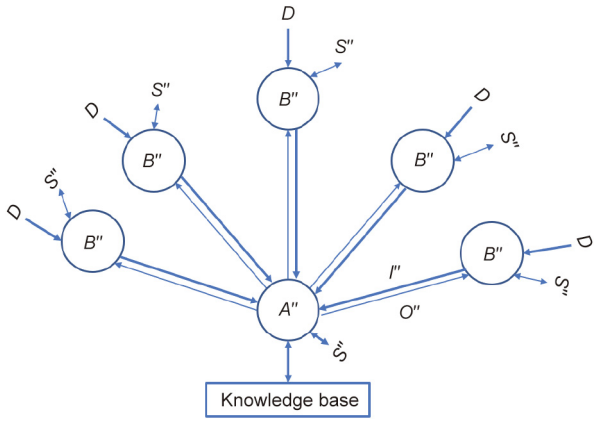

Fig. 5. The basic structure of knowledge absorptive double-layer crowd intelligence. A'': manager of the knowledge base; B'': knowledge provider; D: data flow; I'': information flow of the knowledge provided; O'': information flow of feedback from the knowledge base. In the example, the relationship between type-A'' and type-B'' intelligent agents is that between workers in the entire area and workers in the local areas. However, A'' cannot give instructions to behavior of B'' but can schedule knowledge provided by B''. S'': information flow of communication and perception.

4. The structure of cyclic crowd intelligence systems

The cyclic crowd intelligence system is a crowd intelligence system with cycling resources among various crowds, and the supply–demand cyclic crowd intelligence system is the most important. The platform service system that has been successfully used is now a supply–demand cyclic crowd intelligence system. Its operating mechanism is to build a basic service platform, attract service providers and users to pair with each other independently on the platform, and form a cycle of resources such as services and funds. Its basic structure is shown in Fig. 6.

In Fig. 6, the services provided by the service provider P can be further subdivided. For example, e-commerce platforms have developed from providing products to offering financial services, logistics services, advertising services, and so on. The subdivision of P will contribute to the building of a better service ecology, which is more beneficial to the development of the builder and maintainer of the service platform M, P, and the service user U.

Cyclic crowd intelligence systems can be widely used. For example, e-commerce trading platforms, mobile applications, promotion platforms of financial products, and so on, are all successful operation models of the kind of system.

Example 3: From the perspective of the structure, we can find that the market economy also has the structure of supply–demand cyclic crowd intelligence of platform services. Fig. 7 shows the abstracted structural model of the market economy in Ref. [8].

Compared with Fig. 6, the structure in Fig. 7 lacks the builder and maintainer of market platform M', which should be played by the government. Many governments across the world have successfully played role M'. The crowd intelligence structure of the market economy with role M' is shown in Fig. 8.

Role M' can use laws and rules to guarantee fair market operations and use all of the information to adjust and optimize the

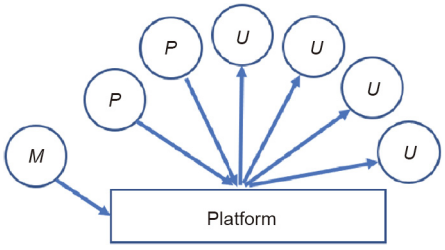

Fig. 6. The basic structure of a supply–demand cyclic crowd intelligence system. M indicates the builder and maintainer of the service platform; P indicates service providers such as merchants on e-commerce platforms; U refers to the service users. The direction of the arrow indicates the flow of services such as product supply, and the opposite direction represents the flow of funds.

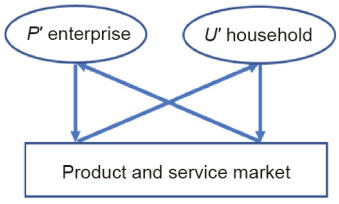

Fig. 7. The structure of the supply–demand cyclic crowd intelligence system of the market economy. Enterprise P' and household U' make transactions in the commodity and labor market to form a supply-and-demand cycle. The direction of the arrow represents the flow of goods and services, while the opposite direction of the arrow represents the flow of funds.

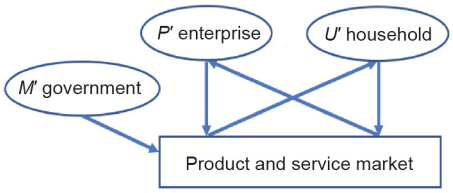

Fig. 8. The double-layer cyclic crowd intelligence structure of the market economy.

market, such as the central bank, scientific research, and development of education and culture. Since there exists a superior-and-subordinate relationship between role M' and roles P' and U', the market economy model with three types of M', P', and U' has a double-layer cyclic crowd intelligence structure.

The double-layer cyclic crowd intelligence structure will probably be an interesting direction of economic research.

5. Incentive and evolution mechanisms

In this section, we will introduce the incentive and evolution mechanisms of crowd intelligence systems and demonstrate that they will change with different types and relationship.

5.1. Incentive mechanism

A well-designed incentive mechanism can help to reduce the uncertainty in crowd intelligence. In crowd intelligence behavior, single-type crowd intelligence systems provide natural incentives according to the efficiency of completing the task. If double-layer crowd intelligence systems involve human factors, the incentive mechanism is essential because it can improve the work efficiency of crowds.

Since crowd intelligence systems with different structures are used for different tasks, there are different incentive mechanisms.

(1) The double-layer crowd intelligence used to schedule actions is suitable for command systems, such as administrative and military crowds. The common incentive methods include education, reward, and punishment.

(2) The double-layer crowd intelligence used to absorb knowledge is suitable for knowledge gathering systems, such as the construction of a knowledge base and database. This type of system can calculate the workload easily, so it often gives rewards based on performance.

(3) Supply–demand cyclic crowd intelligence is suitable for a platform economy. The important point is that the incentive mechanism of this type is different from the previous two. Because supply individuals and demand individuals in the structure can encourage each other, it is a self-incentive mechanism, enabling the supply–demand cyclic crowd intelligence system to have a higher work efficiency and development speed with a lower cost.

5.2. Evolution mechanism

The evolution mechanism of the crowd intelligence system means that the system will change its structure over time, accumulate knowledge, and show progress. It can be divided into two categories.

5.2.1. The internal evolution mechanism of each intelligent individual, such as self-learning and self-reform

As the example in Fig. 8, the internal evolution mechanism of each intelligent individual can be the automation of the production process, management reform of enterprise P' and the increase and decrease of family members, improvement of education level, change of consumption and employment concepts in household U'.

5.2.2. The evolution mechanism of the relationship between intelligent individuals

The evolution mechanisms of the relationship between intelligent agents in the example in Fig. 8 include the following:

(1) Increase or decrease of individual types, such as increasing the number of material or parts manufacturing enterprises in the supply chain and financial, logistics, or business enterprises in the service chain, and so on. Various types of participants often reflect a higher level of specialized division of labor in the system. For example, in the e-commerce platform system, service provider (like P' in Fig. 8) can be further divided into seller P'_1, deliveryman P'_2, financial service provider P'_3, advertiser P'_4, personnel for user portrait P'_5, designer P'_6, and so on. More types of participants can provide higher-level services and improve the collaboration ecology.

(2) Increase or decrease of subdivision of platform, such as increasing the technology market, tourism market, import and export market, and training market. The increase and subdivision of market platforms will directly promote the development of type P' and type U' individuals.

(3) Regulator M' offers prospective, deep support for the development of the whole system. For example, universities, vocational colleges, research institutions, hospitals, conventions and exhibitions, libraries, museums, economic and technological data centers, think tanks, and so on, can indirectly and prospectively promote the development of type P' and type U' individuals.

6. Conclusions

In this paper, we analyzed the general characteristics of different categories of crowd intelligence system structures. Specifically, the structures, mechanisms, and examples of three types of important crowd intelligence systems were fully discussed. We also pointed out that the incentive and evolution mechanisms of crowd intelligence systems should vary with different categories.

References

[1] Surowiecki J. The wisdom of crowds. Anchor: Doubleday; 2005.
[2] Li W, Wu W, Wang H, Cheng X, Chen H, Zhou Z, et al. Crowd intelligence in AI 2.0 era. Front Inform Technol Electron Eng 2017;18(1):15–43.
[3] Frankel F, Reid R. Big data: distilling meaning from data. Nature 2008; 455(7209):30.
[4] Huang HM, Pavek K, Novak B, Albus J, Messin E. A framework for autonomy levels for unmanned systems (ALFUS). In: Proceedings of the AUVSI's Unmanned Systems North America; 2005 Jun 28–30; Baltinore, MD, USA; 2005. p. 849–63.
[5] Wu F, Lu C, Zhu M, Chen H, Zhu J, Yu K, et al. Towards a new generation of artificial intelligence in China. Nat Mach Intell 2020;2(6):312–6.
[6] Pan Y. Heading toward artificial intelligence 2.0. Engineering 2016;2(4):409–13.
[7] Michelucci P, Dickinson JL. The power of crowds. Science 2016;351(6268):32–3.
[8] Mankiw NG. Principles of economics. Mason: Cengage Learning; 2014.