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Supplemental Information

Toward parallel intelligence: An interdisciplinary solution for complex systems

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1. The snowballing literature review procedure

In this study, we have opted for the snowballing literature review method[1,2] instead of the conventional systematic review approach that relies on database searches. This decision was based on three specific reasons:

1) Formulating a precise search proved challenging, as it carried the risk of yielding numerous irrelevant and superfluous publications. Furthermore, our topic's keywords 'parallel systems' and 'ACP' are also utilized in other fields. For instance, in computational science, the parallel system also refers to a system capable of handling multiple tasks or instructions simultaneously. In medicine, the ACP also means Advance Care Planning.
2) The interdisciplinary nature of the research area poses challenges in selecting appropriate databases and constructing effective search strings. Some publications on the parallel systems method do not explicitly use terms such as 'parallel systems, ' 'parallel intelligence, ' or 'ACP approach' in their titles, but instead employ the term 'parallel X' extensively, including parallel learning, parallel sensing, and parallel mining.
3) Snowballing method is comparable to conducting multiple database searches and is particularly useful for expanding existing literature reviews with new aspects. Relevant publications can be continuously found through the citation network, search engine and author network, allowing the included publications to accumulate like a snowball across multiple fields.

We attempted to acquire publications via a database search on Web of Science, however the outcomes were unsatisfactory. For example, we used search string *S*: {parallel systems}, {parallel system}, {parallel intelligence}, {ACP} in our query with a publication date range from 2004-01-01 to 2023-07-01. The search yielded 73,300 publication records, posing a significant challenge for subsequent filtering of relevant publications. Due to the aforementioned reasons, the search results contain a large number of records that are not related to the parallel systems method. More seriously, many publications related to parallel systems method are not included in the search results.

In this circumstance, we employed the snowballing literature review method, which entails two steps: deriving the initial set of topics and conducting snowballing in iterations. The specifics are outlined below:

1) Deriving the initial set of topics.

We selected two preview reviews[3,4] on the parallel systems method and extracted the initial topics from them, including parallel learning, parallel sensing, parallel transportation, etc. Due to the interdisciplinary nature of the parallel systems method, these topics are distributed in various fields.

2) Conducting snowballing in iterations.

Based on the initial set of topics, various methods were employed to obtain relevant publications. More topics were extracted in these publications and driven search for new publications. The following are the methods utilized to acquire these publications:

- Using these topics as search string in the search engines, such as Google Scholar, and screening the results;
- Obtaining publications through the citation and author networks;
- Discussing with experts and asking them to recommend publications.

Through the implementation of a snowballing literature review approach, a total of 215 publications and 53 topics were identified and incorporated into this review. The complete list of publications and topics can be found in the Supplementary Data.

2. Publication analysis

Here, we present the publication analysis of the 215 publications included in this review.

1）Year analysis

The annual distribution of the included publications is shown in Fig. 1. It reveals a general upward trend in the number of publications related to the parallel systems methods. Notably, since the emergence of parallel intelligence in 2016, this growth has been particularly rapid.

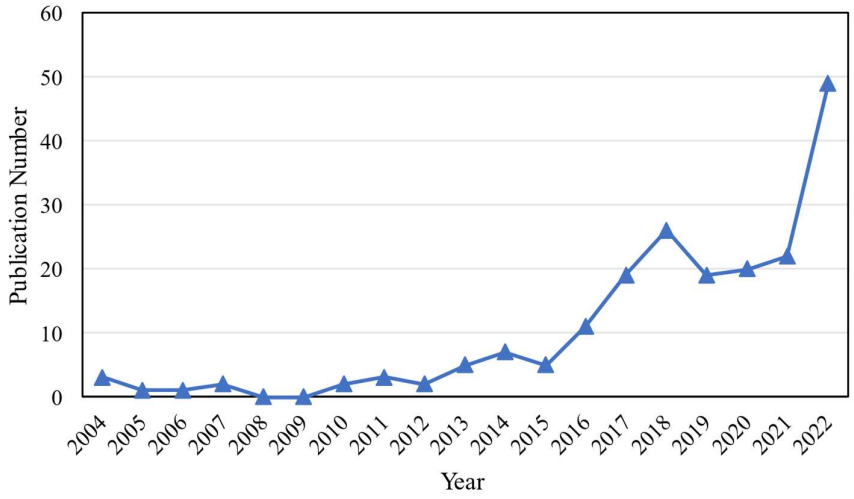

Figure 1. Annual distribution of publications.

We also tallied the quantity of publications that depicted or referenced parallel intelligence, as illustrated in Fig. 2. Since its inception in 2016, there has been a discernible upward trend in the number of related publications.

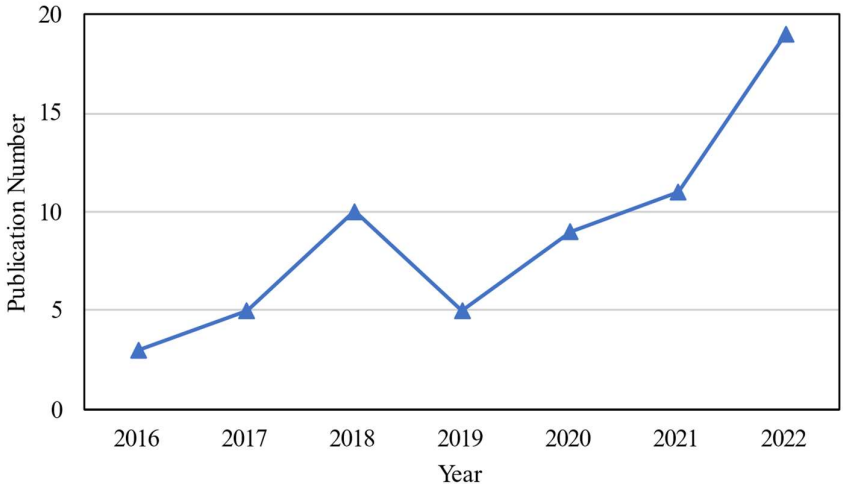

Figure 2. Annual distribution of publications related to parallel intelligence.

2）Topic analysis

We have extracted 53 topics of the parallel systems method from 215 publications. Given that some of these topics were mentioned in multiple publications, we conducted the matching between publications and topics to investigate the heat of topics and the relationship between topics. There are three principles for matching: 1) the topic is mentioned directly in the publication. 2) the topic is not mentioned in the publications, but the content of the publication is related to the topic. 3) the topic mentioned in the publication belongs to a broader topic. For example, publications that discuss parallel vehicles are deemed relevant to parallel transportation as well. Figure 3 illustrates the word cloud map of the parallel systems method based on topics and their frequency in these publications. Note that the ACP approach is not included in the topics since it serves as the technical foundation and be mentioned in each publication of the parallel systems method.

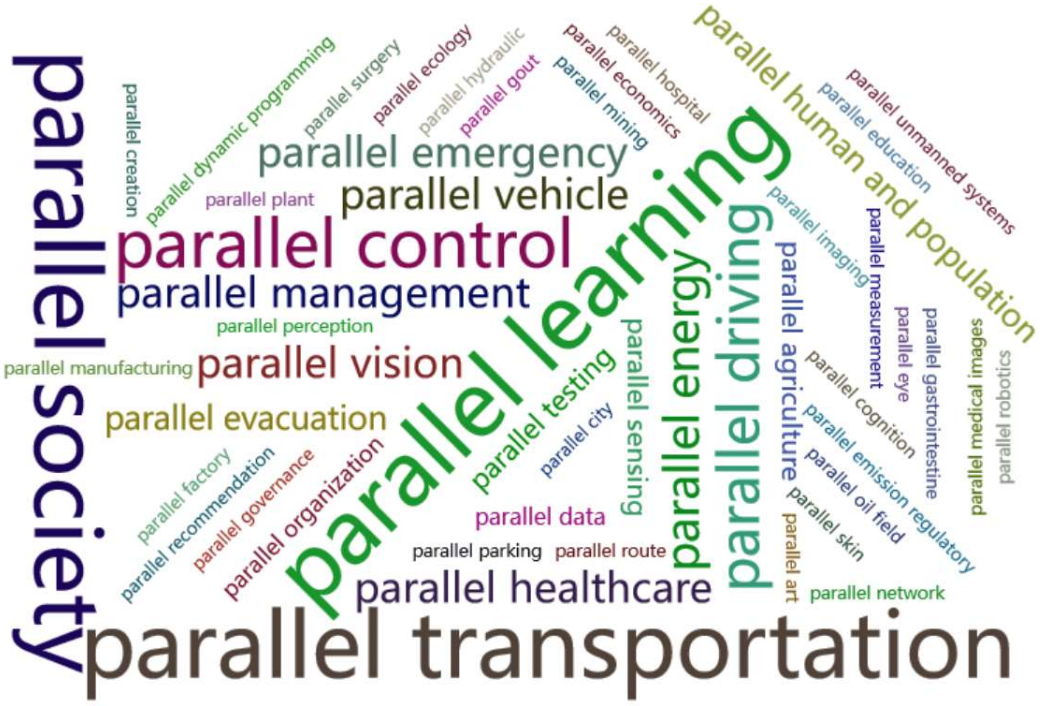

Figure 3. The word cloud of topics.

It is evident that the topics can be categorized into two distinct groups: parallel technologies and parallel applications. The former integrates advanced technologies from diverse disciplines with the parallel systems method to enhance it from different aspects. Meanwhile, the inherent defects of these technologies are alleviated after integrated with the parallel systems. The parallel applications utilize the parallel systems method in various fields to address practical issues, including those related to control and management. The annual distribution of publications of parallel technologies and applications is shown in Fig. 4. As evident, the early publications on parallel systems methods (prior to 2016) primarily focused on parallel applications. In terms of parallel technologies, the early publications are only related to parallel control and management, which reflects the initial purpose for the parallel systems method. However, since 2017, more and more parallel technologies such as parallel learning and parallel testing have been proposed and applied in many fields.

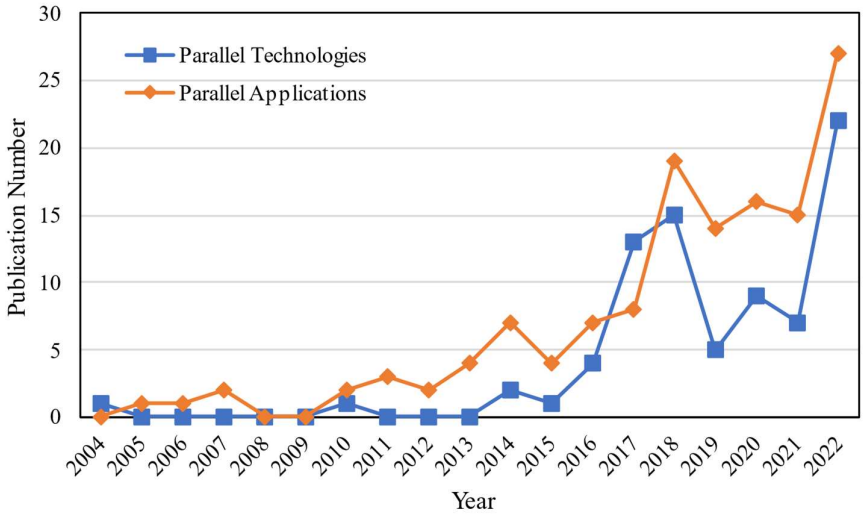

Figure 4. Annual distribution of publications of parallel technologies and applications.

The number of publications on various parallel technologies is presented in Tab. 1. Based on the publication count and content analysis, five major parallel technologies have been selected and introduced in separate sections: parallel learning, parallel blockchain, parallel control and management, parallel sensing, and parallel cognition. Among these, the largest number of publications belongs to parallel learning since its inception in 2017. It is essentially the technical embodiment of parallel intelligence and can provide intelligent decision-making capacity for the parallel systems method. The parallel blockchain is the novel decentralized infrastructure for the parallel systems. It provides a secure and trustworthy environment for the interaction of elements from different spaces within parallel systems. Parallel control and management represent the initial objective and function of the parallel systems method. Parallel sensing is the important technology that mapping elements in the actual system into artificial systems. Parallel cognition represents a crucial stride towards exploring social dimensions through the ACP approach. Despite the limited number of publications on parallel cognition, we have provided a comprehensive introduction to it in this review. Numerous publications exist on other parallel technologies, including parallel vision, parallel testing, parallel organization, and parallel data. However, there is some overlap

between the publications of these technologies and those of the five major parallel technologies, and their concepts or implementations exhibit similarities with those of the five major parallel technologies. For instance, the parallel learning is the important supporting technology for both parallel vision and parallel data. Therefore, to be concise, only the five major parallel technologies are presented in a separate section while other parallel technologies are integrated into the introduction of these five major ones.

Table 1. The number of publications on different parallel technologies

Topics	Publications Number	Topics	Publications Number
parallel learning	37	parallel data	6
parallel blockchain	18	parallel cognition	5
parallel control	18	parallel measurement	4
parallel management	15	parallel dynamic programming	3
parallel vision	14	parallel imaging	3
parallel sensing	7	parallel perception	3
parallel testing	7	parallel governance	1
parallel organization	6		

We have categorized the majority of parallel application topics into five fields: parallel transportation, parallel industry, parallel society, parallel healthcare, and parallel agriculture as presented in Tab. 2. In this review, we provide a comprehensive overview of these five fields with a detailed introduction to their respective applications. Although the number of publications in parallel agriculture is limited and the scope of topics covered is narrow, they still be introduced in detail. These publications have established a comprehensive framework for this field, providing a solid foundation for its future development. Furthermore, certain topics related to parallel applications do not fit within the aforementioned five categories, such as parallel art and parallel education. Due to limited literature in these fields, we have refrained from dedicating a separate section to them.

Table 2. The five major fields and their topics

Fields	Topics	Fields	Topics
parallel transportation	parallel vehicle	parallel society	parallel city
	parallel driving		parallel economics
	parallel routing		parallel evacuation
	parallel parking		parallel emergency
	parallel recommendation		parallel human and population
	parallel emission regulatory	parallel healthcare	parallel gastrointestine
parallel industry	parallel mining		parallel gout
	parallel energy		parallel eye
	parallel factory		parallel surgery
	parallel hydraulic		parallel skin
	parallel oil field		parallel hospital
	parallel manufacturing		parallel medical images
		parallel agriculture	parallel plant

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