Distributed Consensus and Group Intelligence

The proposal tries to explore the essence of 'distributed' to achieve more advanced group intelligence in future distributed computer and control systems.

This is without doubt a broad topic. But some existing research concerning distributed scenarios may provide interesting inspirations and possible focus. In human society, cognitive consistency theory is a representative social psychological theory that demonstrates humans in society always pursue a balanced and harmonic inner mind to develop their intelligence [12]. Additionally, in distributed computer systems, the consensus theory plays the dominant role to secure safety and liveness [6]. Consensus is considered as one of fundamental cores in a large number of applications of distributed computing such as distributed database, federated learning, and blockchain. Moreover, there is another consensus theory prevalent in control based on dynamic equations to average values of edge devices for consistency [10]. Many control problems in Multi-agent Systems could be considered as applications of consensus, such as rendezvous, alignment, swarming, flocking, containment control, and circumnavigation control [14]. Considering human society, distributed computer systems, and cooperative control systems, it seems that consensus generally shows its significance in the philosophy of 'distributed' to achieve group intelligence.

However, there are gaps and differences in the consensus theories of these three systems. Firstly consider the consensus in computers (CCP) and the consensus in control (CCT). CCP originated from the safety critical systems in aerospace, then developed in distributed computer systems. It guarantees safety and liveness with complex mechanism design, achieving consistency ranging from the strongest to the weakest, as well as termination. It could also be used to deploy blockchain for fairness and privacy-preserving. Another theory, CCT, has strong partition-tolerance, suitable for edge devices such as sensors, but could only achieve the eventual (weakest) consistency and has no termination [13], demonstrating the trade-off in CAP theory [3]. As for the consensus in human society, the difference between it and other systems is clear: each parity in computer systems and control systems not only has weak individual cognition and intelligence (inner factor), but also is strongly limited by their powerful owners (outer factor). This implies it is far away for them to achieve a group intelligence as advanced as human society.

It seems that human society, distributed computers, and cooperative control systems are generally in a descending order in terms of intelligence level. Thus this proposal tries to fill the gaps and improve them, especially the distributed computer systems and control systems. The first idea involves the gap between computers and control systems: **to achieve more reliable group intelligence**. The second idea is the gap between human society and other systems: **to achieve more cognitive group intelligence**. In this proposal, the first idea as well as the challenges will be discussed in detail, while the second will only be briefly described.

As for the first gap, the boundary tends to be gradually disappearing nowadays. Some work has applied CCP in the control scenarios for high reliability. [1,9,16] apply Byzantine fault tolerance to ensure a high degree of security of smart power grid monitoring and control.In [2,4,7], Byzantine fault tolerance with veto collection and gossip stages are designed to meet the stringent and complex requirements for Internet of Vehicles. It is worth noting that today's Cypher-Physical Systems (CPS) involve both network interactions and physical control to achieve more advanced group intelligence, leaving spaces for tight combinations of these two areas. For example, how do robots or edge devices know whether their missions will be accomplished timely and safely? Whether do safety and liveness serve as the foundations of more advanced group intelligence? Just imagining the hardware level of future edge devices to be developed as advanced as computers, CCP seems reasonable to be applied in future control systems and CPS, such as cooperatively maintaining the global sensing data and calculated results, or improving the aggregation of the preferences to make consistent decisions.

Besides application scenarios, there are possible inspirations for the development of consensus theory. It seems that the variety of Validity definitions in consensus could map into different CPS environments. In [13], the Median Validity is proposed for the byzantine agreement problem with orderable initial values to the median of the initial values of the non-byzantine nodes. My previous work (under review) proposed Voting Validity concerning social choice and preferences aggregation in decision-making based on consensus. [8] proposed the Interval Validity referring to the k-th smallest value of the correct nodes. This could be extended to multiple dimensions to determine a value that lies within a box around all correct input vectors. In [5], the property of Order Fairness (analog to Validity) is proposed and shows the need for fair transaction ordering in BFT when looking at financial systems. These proposed state-of-the-art consensus theories fuse with thinking such as decision-making, range bound, sorting, and median, which have the potential to be applied in CPS. On the other hand, CPS applications for group intelligence could also stimulate new elements in consensus theory.

The challenges in this topic may involve the following aspects.

(1) **Control and consensus**. Although the boundary is gradually disappearing nowadays, existing research usually directly uses CCP in CPS applications. However, the trade-off between consistency and performance (CAP theory) in distributed systems is a long-term challenge for researchers and it should be carefully designed and optimized in specific distributed scenarios. Since CCP pursues reliability while CCT is prone to applicability, maybe the hybrid strategy could be adopted according to the significance of data and decisions to achieve a balance. Additionally, CCT and CCP could consider complementarities in theory, e.g., whether the principles or theoretical elements in one area could bring inspiration to the other area.

(2) **Consensus network analysis and optimization**. With the widespread of distributed applications such as Internet of Vehicles, CPS, Metaverse, and blockchain, the consensus network may involve massive expansion. Considering the complexity of the consensus protocol, especially BFT protocols, the basic performances of the network need to be discussed and analyzed, such as topology optimization, network flow, delay, reliability, etc. It seems that the information theory in complex network may act as an interesting analysis tool for fundamental problems such as at least how much information bits the network is required to achieve BFT consensus.

(3) **Communication in consensus network**. Effective information exchange is significant in both CCP [11] and CCT [15]. Wireless communication is unavoidable for edge devices in CPS, where the impacts of the potential unreliability of wireless communication to consensus should be evaluated. My previous work (under review) analyzes the wireless consensus network reliability in CCP. Particularly, the explosive queuing latency could be caused even by a minor consensus failure rate due to the SMR mechanism. This implies that communication and consensus co-deign might be the next step, such as wireless resource and communication optimization for reliable consensus, or the consensus mechanism design resistant to impacts of link loss.

(4) **Computation in consensus**. CCT has wide applicability for edge devices, but CCP usually has a complex mechanism. Although our previous research team has implemented RAFT/PBFT-based Internet of Vehicles in the embedded system, the computation is expensive and may not be suitable for some edge devices such as sensors. Cloud computation seems a powerful solution to alleviate the computation burdens.

The second part is to achieve more cognitive group intelligence. This may involve the gap in consensus theories between human society and computer/control systems. One clear challenge is that the latter only has **weak individual intelligence and lack of cognition**. Even so, they are still strictly controlled and limited by humans. Future AI might be a powerful solution. It is interesting to see the combination of future distributed AI and the considerations of safety and liveness in consensus or other inspirations in cognitive consistency theory.

This proposal discusses one similar concern in different distributed scenarios including humans, computers, and control systems: consensus. Then it considers possible research in terms of theory and applications. Many directions and challenges might be mentioned above in this topic, but it would be more beneficial only to consider two or three challenges in the Ph.D. research journey. Maybe one or two years for one challenge is suitable to explore in a decent depth.

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