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Emerging Self-Integration through Coordination of Autonomous Adaptive Systems

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***Abstract*—The self-improving system integration initiative emerged as response to the ever growing complexity in large-scale open constellations of systems. Especially in the context of a set of self-adaptive systems working together in an overall system-of-systems, integration is a very complex task due to the limited predictability of system behaviour. In this position paper, we argue that one approach to tackle the problem can be found in an adaptive coordination of autonomous adaptive systems. Therefore, we characterise existing coordination approaches and identify four research challenges that need to be addressed. We use the scenario of platooning of autonomous vehicles to demonstrate the resulting challenges.**

***Index Terms*—system integration, autonomous systems, self-adaptation, emergence, coordination**

I. Introduction

Recent trends such as Internet-of-Things (IoT) [1] or cyber-physical systems (CPSs) [2] require the integration of many different entities, resulting in systems-of-systems [3] or even interwoven system [4] constellations. The integration of these large scale, heterogeneous entities in a way that a common objective is obeyed is a very challenging task [5]. Additionally, characteristics of these systems as mobility—which results in on-going changing environmental conditions—influence the system performance and increases the complexity.

Establishing self-adaptive systems (SASs) [6] aims at handling (i) the dynamics resulting from changing environmental influences and (ii) the complexity in the interaction of the heterogeneous entities with adaptation. Usually, SASs are implemented as software solutions being able to change their behaviour at runtime, which allows for dealing with dynamics in the environmental conditions, internal failures, and changing interaction partners. The term comprises several initiatives and their corresponding system design concepts such as self-aware computing [7] (i.e., the LRA-M model [8]), organic computing (OC) [9] (i.e., the Observer/Controller model [10]), and autonomic computing (AC) [11] (i.e., the MAPE-K cycle [12]). The general adaptation behaviour is defined in terms of a control loop, typically consisting of the steps monitoring the system and its environnment, analysing, i.e., identify problematic changes in the environment and the system, planning necessary adaptations, and control the execution of these adaptations. This is typically supported by a (shared) knowledge repository.

These concepts mainly focus on the control of an individual system and mostly allow for self-adaptation depending on a local scope and a local utility. In terms of self-integration into large-scale systems-of-systems, this raises another issue: Since these resulting systems might be composed of collaborating autonomous systems [13], the decisions of one system have impact on those of others (neighboured) systems. Consequently, the integration of others are affected from local decisions. In case of all systems trying to achieve a common goal, this is not an issue; but it is if local goals are competitive or even conflicting but act collaboratively in a shared environment. Consequently, it is important to adjust the adaptations of the local sub-systems for avoiding contradicting local adaptations for fostering the emergence of the common global behaviour. This common behaviour enables the integration of several adaptive sub-systems.

In this position paper, we discuss different approaches for coordination of autonomous entities that might be applied for emerging system integration of autonomous, adaptive entities. We take the behaviour of the entities, information dissemination, negotiation, rewards, and leader-based coordination into account. Further, we identify key design aspects of these approaches such as degree of centrality, communication overhead, and robustness. We specifically target the necessary adjustment of adaptive behaviour and discuss several mechanisms for this.

The remainder of this position paper is organised as follows: Section II briefly summarises the concept of hybrid collaborating adaptive systems. Afterwards, Section IV discusses different coordination mechanisms w.r.t. their suitability for system self-integration. Section V derives specific challenges for coordination in such hybrid systems. Finally, Section VI concludes the paper.

II. Hybrid Collaborating (Self-)Adaptive Systems

Self-adaptive systems are systems that react to changes in itself or the environment by changing their behaviour at runtime [6]. Central components of self-adaptive systems are the adaptation manager (AM) – which implements a control structure; often based on the MAPE-K functionality – and the any software or hardware managed resources (MR).

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Implementing the AM on different levels will result in varying degrees of autonomy for the resources.

The implementation of one central AM would enable globally optimal planning benefiting from extensive information about the system. However, this conflicts with the concept of spontaneous self-improving systems. In addition, the globally optimal actions may contradict the goals of the individual subsystems, and they may oppose the decision.

In contrast to the central AM, in a fully decentralised approach each resource has its own dedicated AM that plans its actions without any knowledge of the other resources. This may lead to non-optimal states for the global system, as each entity tries to optimise its own goals. However, the entities cooperate fully autonomously, i.e., they fulfil common tasks, compete for resources, or coexist. Coexistence is present when the autonomously planned interactions are not coordinated but do not have conflicting goals.

In between, a hybrid approach combines the advantages of both extremes. In a hybrid approach, some MAPE functionalities are centralised, while others are decentralised. For example, decentralised planning could be implemented with information exchange, so that all local AMs know the states, goals and actions of the other AMs.

Depending on the approach, AM and MR are implemented on different levels, and the AM are equipped with corresponding functionality. Our previous work [14] presents a formal system model defining the different levels.

III. Running Example: Platooning

As a running example for a self-adaptive system, we introduce platooning, which is an approach in the area of autonomic driving, where the vehicles are coordinated. The semi-automated vehicles drive in convoys, maintaining a distance of a few meters [15]. For a vehicle to be identified as semi-automated, they have to control at least the longitudinal distance without user interference or in the best case, drive fully autonomously. As the vehicles decide about their driving behaviour, they can be considered as autonomous systems. So, a platoon consists of autonomous entities and coordination is required to achieve a common behaviour. The autonomous vehicles can be seen as a self-adaptive system that is integrated into a platoon-system, that is again self-adaptive.

Finally, this platooning example can be mapped to the previously mentioned levels at which the AM can be implemented. Global optimal planning can be ensured with one central AM that knows all vehicles and platoons with their according routes and goals [16]. This AM would plan the routes and thereby the creation of platoons regarding a global utility function. The individual goals may conflict with the global optimal plan. In contrast, when the AM is implemented decentrally, each vehicle would have its own AM and plans only targeting its own goals, and a global optimum may not be achieved. So, a hybrid approach where the vehicles are autonomous and have their individual AM but with additional communication and information exchange may be advantageous.

IV. Coordination Mechanisms

This section discusses several coordination mechanisms w.r.t. their suitability for system integration. In detail, it present selfish and altruistic approaches based on information dissemination, hybrid approaches based on negotiation and rewards, as well as central decision making using enforcement of decisions. Whereas the information dissemination and negotiation approaches are applicable in fully decentralised scenarios, the others require a (temporary) regional/central leader. All approaches achieve a shared global behaviour that emerge from the behaviour of individual entities. These coordination mechanisms can integrate different adaptive subsystem elements that act as SASs.

A. Purely Decentralized Approaches

Selfish behaviour. As a first approach for purely decentralised decision making of autonomous entities, we assume that selfish behaviour might lead automatically to a coordination of the instances due to interaction awareness [17]. This interaction awareness triggers that instances are aware of influencing each other and, hence, they are motivated to coordinate each other to achieve the highest benefits. Hence, each entity tries to optimise its benefits through coordination with others. Information dissemination can help to lower the risk for potentially conflicting decisions. Still, this group of approaches does not make use of explicit coordination or management mechanisms. In turn, the system is fully decentralised and the resources act fully autonomously without the usage of explicit coordination or negotiation techniques. For coordination purposes, this generally refers to simple scheduling schemes, e.g., first-come-first-serve (see [18] for an overview). Alternative solutions include Organic Computing concepts, e.g., [19].

Altruistic behaviour. Further, to overcome the issue of conflicting adaptation plans if selfish entities are not interaction aware, they need to be convinced to act altruistically for global welfare [17]. In other scenarios, resources might always act altruistically, e.g., for scenarios in which self-driving vehicles follow a defensive driving behaviour and that are coordinated through communication. Such resources with altruistic behaviour always try to adjust themselves in a way that global welfare is optimised. Again, this can lead to conflicts as adaptation decisions are not coordinated. Information dissemination can support the adaptation decisions and coordinate them implicitly.

Negotiation. As described, information dissemination can support the controlled emergence of global behaviour for both settings, selfish and altruistic behavioural resources. Several situations can occur, where agents may not agree, but still need to find a consensus, i.e., a solution that everyone accepts, even if it is not everyone's favourite choice (e.g., [20]). This helps to achieve overall system reliability in the presence of a number of disagreeing agents. In general, this is referred to as "consensus problem" [21]. Approaches to tackle this include protocols (e.g., the Terminating Reliable Broadcast protocol [22] or the Contract Net protocol [23]), negotiation techniques, mechanisms such as auctions [24], or bio-inspired approaches (e.g., [25]).

B. (Pseudo-)Central Approaches

There are scenarios where a central or pseudo-central instance is necessary, e.g., if decentralised coordination might result in conflicts. In the following, we briefly describe such two approaches.

Enforcement of decisions. Approaches based on leader election for choosing one specific node that acts on behalf of the group (see e.g., [26] for an overview of algorithms) can help to enforce a central plan. Hence, the coordination problem is handled in a centralised manner with the leader deciding about the current strategy. However, fairness must be given, i.e., the leader should not act selfish and discriminate against the other resources. Examples for fairness metrics include [27] or [28].

Rewards. A similar approach integrates rewards for resources. Here, also a (pseudo-)central approach enables the alignment of adaptation decisions of the resources to a global objective. However, instead of forcing the resources to obey a given plan, rewards functions convince the resources to choose from a set of adaptation alternatives specifying degrees of freedom. This is a mix of a selfish and central approach: each resource tries to optimise its benefits but the central planning enables the compliance to a global objective and given global constraints.

V. Research Challenges

Based on the coordination mechanisms presented in the previous section, this section discusses the suitability of the approaches in different settings for self-improving system integration. We highlight the complexity of the research challenges using the example of platooning presented in Section II.

Degree of centrality. There are several reasons why a centralised (even a pseudo-centralised solution based on leader election) is not used in specific cases: single-point-of-failure, exploitation of power, communication overhead, or a variety of attack vectors. Consequently, decentralised approaches have been a promising alternative, see, e.g., [29]. Contrary, there might be situations in which a consensus of adaptations to global objectives is only possible using a central setting. Regarding system integration, usually decentralised approaches might be preferable as the target domain is large-scale systems-of-systems. Pseudo-central approaches might be a suitable alternative as they ensure the compliance of the sub-systems' behaviour to a global behaviour. Such approaches could be implemented as regional approaches with several clusters having (temporal) leaders, which could coordinate cross-regional.

In the platooning example, one has to distinguish two situations. First, the action of searching for a platoon requires the dissemination of the information, which platoons are available. Depending on the degree of autonomy of the vehicles, the decision which platoon a vehicle joins can be taken decentrally by the vehicle itself or by a central broker system (cf. [16]). Second, after joining a platoon, the coordination within a platoon is purely centralised as the leader of the platoon defines the speed and route. Third, inter-platoon interactions again can be centrally or decentrally organised.

Communication overhead. The different approaches for coordination require a different amount of communication, which is also influenced by the degree of centrality. Fully decentralised, non-coordinated approaches do not communicate at all for the coordination. However, this increases the probability of conflicts. Central approaches optimise the adaptation, hence, the process of self-improving system integration. However, this comes with the disadvantage of communication overhead as the leader has to collect all information and the decision needs to be spread across entities. Decentralised, coordinated approaches require even more information, as some or all entities have to collect the information for decision making and spread the decision. As a rule of thumb, one could say that the more entities are involved in the decision making process, the higher the communication overhead can be. The challenges here lies in the trade-off of balancing the communication overhead with the achievable global optimisation in decision making. For a global optimisation, a high communication overhead for information exchange is necessary; vice versa, required information is reduced for local optimisation with the potential for conflicting, non-coordinated behaviour.

The platooning example requires a high amount of intra-platoon communication for maintaining the distance between the vehicles of a platoon (decentral adaptations) as well as vehicle-to-vehicle (decentral decision making) or vehicle-to-infrastructure (central decision making) communication for initially finding a platoon. Both tasks have to rely on information dissemination for coordination. Here, the communication range is another factor. Decentral decision making for which platoon to join, i.e., each vehicle collects information on available platoons, requires a high degree of information as the communication range for vehicular communication is limited.

Impact of coordination Related to the degree of centrality and the communication effort is the impact of coordination. Coordination can have a local impact, i.e., instance-based in case of no coordination impact at all or sub-system wide impact, or in the optimal case for system integration a global system-wide impact. For decentralised settings, a high communication effort is required to achieve a global impact of coordination. Centralised settings require altruistic entities or the use of rewards to achieve a global impact of the coordination as otherwise the autonomous entities might disobey central decisions. Hence, there is on the one hand a trade-off between the impact that should be achieved and the effort. On the other hand, the impact might have different levels as some aspects for system integration have a local impact only, while simultaneously other aspect target the whole systems, i.e., have a global impact.

In the platooning use case, we assume that platoons do not have uniform properties in term of velocity, which might be the case for truck-only platooning approaches. In such settings, a central coordination unit can optimise the search for platoons and have a global impact. Still, decentralised coordination enables system integration as vehicles can join platoons albeit the platoons might not be composed optimally[1], i.e., the decision have a local impact.

Robustness of coordination. Typically, coordination decisions are either the result of negotiations among autonomous systems or optimised plans provided by centralised entities. In both cases, they usually describe single points in the search space. Depending on the underlying utility function, these solutions may be characterised by instability if the behaviour of at least one of the coordinated systems differs from the plan. Consequently, a challenge is to identify more robust solutions in terms of optimised points in the search space without large drops in the fitness functions (i.e., a plateau).

For the platooning example, robustness of coordination is important especially in scenarios in which the assignment of vehicles to platoons take place without a central coordinating unit. Constant optimisation of the platoon membership, i.e., re-negotiation of platoon assignment or changes of positions within platoons (which influence the fuel saving effects through slipstreams), can decrease the performance and effects of platooning due to the required driving actions. Hence, platooning is an example that extremely benefits from robustness in the coordination process.

VI. Conclusion

In this position paper, we present a concept to emerging system integration of autonomous entities. Each of these entities is an autonomous adaptive system. However, as they share a common environment and global objectives, it is important to integrate their behaviour. We compare coordination approaches based on the assumption of selfish and altruistic behaviour of the entities, information dissemination, negotiation, rewards, and leader-based coordination. All of these coordination approaches relate to four research challenges, namely (i) different required degree of centrality, (ii) required communication, (iii) varying impact of coordination for system integration, and (iv) robustness. As future work, we plan on further formalising the problem of emerging system integration though coordination coordination and studying the applicability of the coordination approaches in different system settings conforming to the discussed research challenges.

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