Should I Stay or Should I Go? How Constituent Systems Decide to Join or Leave Constellations in Collaborative SoS

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***Abstract*—A collaborative system of systems (SoS) is formed when independent organizations decide to cooperate to achieve mutual benefits, while retaining independence of their respective systems. Each constituent system (CS) of the SoS has a set of capabilities, some of which they agree to potentially use in active collaboration with others. Such an active collaboration is called a constellation and can be seen as an instantiation of the SoS which is created to provide a joint capability. Constellations are thus the working-horses of the SoS, but due to the operational independence of the CS, they have a choice whether to join a certain constellation or not. This paper discusses the reasoning and world model that is necessary for a CS to make well-informed decisions to join and leave constellations. We argue that it is necessary for the CS to understand not only the surrounding environment, but also to have models of other CS' world models as well as of their probable future actions. It must be possible to predict whether other participants will uphold their parts of the collaboration or may defect from it to join another more rewarding constellation despite the agreements made when joining the SoS. The reasoning in the paper is illustrated using examples from two different collaborative SoS in the transportation domain.**

Keywords—Collaborative system of systems, Constellations, Situation awareness, World models

I. INTRODUCTION

From its roots in the defense sector, systems of systems (SoS) research has lately expanded into many other domains leading to a breadth of both SoS characteristics as well as many new solution patterns and engineering techniques. A key aspect of SoS is the operational and managerial independence of the constituent systems (CS) [1], which creates an interesting dynamic in the structure of SoS, which we believe is not yet understood sufficiently.

The degree of CS independence varies between different SoS, and a commonly used classification was provided by Maier [1] and later extended by Dahmann and Baldwin [2]. The main categories are directed, acknowledged, collaborative, and virtual SoS, with increasing CS independence in the latter categories. The key aspect here is the interpretation of "independence", which we take to mean that the operator or owner of a CS decides when it should join or leave the SoS, and how to collaborate with other CS, subject to constraints that are agreed upon when first joining the SoS. While this independence is explicit in collaborative SoS, it is also present in directed and acknowledged SoS: at some point in time, the owner and/or operator of a CS agrees to join the SoS.

In the defense domain, directed and acknowledged SoS are most common, and the CS decisions are mainly whether to join or not join the SoS at all. Once joined, the CS agree to be directed by the SoS operator, and hence give up their independence regarding operational decisions. For this reason, defense SoS dynamics is typically framed as an acquisition problem.

Civilian SoS, on the other hand, are often collaborative and thus CS retain their operational independence. Hence, the spread of SoS to new domains motivates a deeper understanding of the consequences of increasing CS independence, as is seen in collaborative SoS, which are the focus of this paper. It should also be noted that even in the defense domain, there is a need to better understand collaborative SoS, as they relate to mosaic warfare and network-centered warfare, where the goal is to be able to combine systems more dynamically.

A collaborative SoS is formed when independent organizations decide to cooperate for mutual benefits, while retaining independence of their respective systems. The individual CS may thus have different owning and operating organizations, and management of the SoS is often handled by a consortium of several organizations. Each CS has a set of capabilities, some of which they agree to potentially use in active collaboration with others. Such an active collaboration is called a constellation [3], which can be seen as an instantiation of the SoS. In addition to the CS, there could also be mediators and infrastructure that are necessary to enable the collaboration in constellations.

Constellations are the working-horses of a SoS. In the terminology introduced by Martin [4], the joint capabilities of a constellation perform an intervention that aims at solving a need. The intervention could be intended to address the needs of external users or to give mutual benefits to the organizations that participate in the SoS. We will give examples of both kinds of needs in section V.

In previous work, we have studied the situation awareness needs of a CS [5].We now turn to the question of how a CS can decide whether to cooperate with others or not. The main contribution of the paper is a description of the reasoning and world model that is necessary for a CS to make well-informed decisions to join and leave constellations.

The remainder of the paper is structured as follows: we start by reviewing some terminology and life-cycle characterization of CS. Sections on decision-making for socio-technical agents, the notion of capabilities, and two examples of collaborative SoS where the CS face different decision-making challenges come next, followed by section VI where we put it all together by discussing the decisions to join and leave a constellation. We conclude by reviewing some related work and giving conclusions and suggestions for future work.

II. MEDIATORS, CS STATES AND CONSTELLATIONS

Before going into the core contribution of this paper, namely how CS make operational decisions, some

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This work was carried out in part within the MAUS project funded by Vinnova, Sweden's Innovation Agency (grant no. 2019-05100).

terminology and concepts need to be introduced, which is based on [3]. In addition to the CS, there can also be a need for mediators, *i.e.,* elements that help the CS to collaborate, and who do not have an independent purpose outside of the SoS. At any instance of time, some of the CS in the SoS will be actively collaborating while some will be pursuing only their individual goals. A set of CS that are actively collaborating is called a constellation. A CS can in principle be part of two or more constellations simultaneously. Membership of a constellation can change – some CS might be involved for the entire existence of the constellation, whereas others only join for a short duration.

A CS can be in different states with respect to its knowledge of and cooperation with the SoS. Initially, the CS is *ignorant*, meaning that it has no relation whatsoever to the SoS. To be part of the SoS, it must first ensure that it fulfills the requirements, and when that is achieved it becomes *prepared.* While the focus in this paper is on collaborative SoS, we note that the distinction between an ignorant and a prepared CS holds true even for virtual SoS – consider for example the Internet as a virtual SoS and a computer as the CS. The transition from ignorant to prepared then corresponds to adding networking functionality to the computer.

Once the CS has joined the collaborative SoS it enters the *passive* state, where the agreements are in place for collaborating with others, and it can exchange information about forthcoming collaborations, but where no such collaboration has yet started. The CS is thus continuing with the operation it had prior to joining. Finally, it can become *active*, which is when it is part of a *constellation*, *i.e.,* a subset of CS that combine their capabilities in order to deliver a joint capability that is part of the SoS mission.

Once in a collaborative SoS, a CS typically alternates between the active and passive states. However, the CS (or its operating organization) may also choose to leave the SoS altogether to become prepared, or even ignorant, again. Note also that a CS may be part of several SoS, or join several constellations within one SoS, simultaneously.

The conceptual model of [3] also shows how the decisions form a hierarchy with macro, meso, and micro levels. The *macro* level is typically dealing with the SoS as a whole, and about management decisions on investing in preparing CS for the SoS. The *meso* level deals with management decisions on joining the SoS, and the *micro* level focuses on the operational decisions related to joining or leaving constellations. In this paper, the focus is on the micro level, but it is important to realize that the levels are interrelated. A meso level decision to join the SoS depends on the expected benefits of being a member, which depend on how operational decisions are made. At the same time, the operational outcome for a CS depends on what other CS have also decided to join, so it depends on the meso decisions.

III. DECISION-MAKING

There is a large body of research in the field of decision-making, ranging from descriptive work (how do humans actually make decisions) to normative prescriptions (how should decisions be made). Decisions are often made under uncertainty [6], which complicates the analysis.

In this section we will present some basic structure for what a decision can be based on. All of this information must be present in the world model of the CS in order for it to make decisions. The most obvious are goals– an agent wants to take actions that bring it closer to reaching its goals. Goals can however be conflicting, so that reaching one goal might make it impossible to reach another, either because the goals are incompatible with each other or because the actions needed to reach them make use of the same resources.

An agent, such as a CS, gets goals from several different sources. Some come from the overarching goal of its owner and operating consortia, *e.g.,* making money or promoting the image of being a "green", environmentally friendly company. Others arise during the execution of an assignment, *e.g.*, an intermediate goal to deliver a passenger to their home in time to be able to reach a school to collect children for transport home when their school day ends. The goals are connected to the interventions mentioned above. A CS that participates in a collaborative SoS has goals to help implement the interventions for which the SoS was designed.

Another category of basic data on which to base a decision are rules and regulations. These too can be conflicting and be in conflict with goals. Agents acting in society must adhere to the laws and regulations imposed by society or face the consequences. Agents must take account of these rules, and either follow them stringently or determine if breaking them in order to reach other benefits is worth the cost. In the short perspective, agents do not have the option of leaving society in order to avoid the cost of breaking the rules – there is no provision for either individuals or companies to leave the implicit societal contract. The process for changing the rules is long and complicated, since the rules are determined by the political bodies of the society in which the agent acts.

In addition to rules imposed by society, there are also rules that are voluntarily agreed upon. Standards and rules of operations that collaborating agents agree upon are examples of this. These rules are somewhat easier to change since they are decided closer to the agent. It is also easier to leave the agreement – and hence such agreements must include penalties for agents that wish to leave them.

Another perspective that is in some sense intermediate between goals and rules are values. Every decision that is made is based on values. This is a consequence of Hume's law [7], that an ought (a value judgment) cannot be inferred from only what is (facts). Some values are encoded in laws and rules (*e.g.,* the value judgment that one should not kill unnecessarily). Others have not been codified but are shared by most entities, while there are also values that are specific to an organization.

Finally, it is not enough to have goals, rules and values. The agent must also have facts on which to base the decision. This can be gathered by communication with others and sensing, leading to situation awareness represented in a world model.

If the agent is in an environment where there are several actors, it can communicate with them and use the information received as further basic facts. However, it must be aware that this information might be incomplete, uncertain, biased or even false. The reasons for this range from uncertainties in data and honest mistakes over competing companies not wishing to share all information to deliberate deception. In military intelligence, it is standard to classify information according to its credibility and the reliability of its source. Credibility is assigned a numerical score between 1 (confirmed by other sources) to 6 (trust cannot be judged),

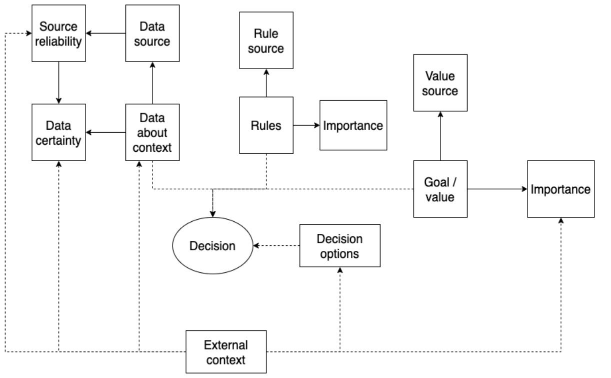

Fig. 1. Overview of factors that must be taken account of in decision-making and hence included in the world model of a CS. Arrows indicate a "has-a" relationship and dotted arrows indicate an "influences" relationship. Thus, the External context influences the Decision options which in turn influence the Decision, while Data about the context has both a Data source and a Data certainty.

while reliability varies from A (completely reliable) to F (reliability cannot be judged) [8]. Similar characterizations of information received by an agent needs to be made, and appropriate fusion methods that take uncertainty into account applied in order to produce situation awareness in the agent.

A summary of the influences of a decision is shown in Fig. 1, which graphically presents the structure presented in this section. Note that this decision-making structure is valid for any socio-technical system that makes decisions – it applies equally well to a human or computer agent. In order to make well-informed decisions, the CS must have a world model that includes all the factors mentioned above and illustrated in Fig. 1. In addition, the world model must also include information about other entities, ranging from their positions to their intentions and capabilities.

IV. CAPABILITIES

As mentioned above, the purpose of a constellation is to realize a capability of the SoS, by combining the capabilities of the CS that form the constellation. The importance of capabilities is also apparent in the recent international standards, that define SoS as a "set of systems [...] that interact to provide a unique capability that none of the CS can accomplish on its own" [9]. The same standard defines capability as a "measure of capacity and the ability of an entity (...) to achieve its objectives". Although this definition of capability captures the essence of the term, we believe that additional precision in terminology is needed to use it as a basis for analysis. This is also in line with the conclusions of [10], that there are many different views on what capability means, that are all plausible.

We view capability as a combination of a process and some resources. The *process* is a function that takes time to complete or that continues over a time period, and its effect is to alter the state of some objects in the world. A set of *resources* is necessary to perform the process, and this defines the capacity. Those resources can be of many kinds, and include both consumables (e.g., energy), and equipment that is reserved when used but available for other uses when the function has been performed. Information is a third type of resource, which is neither consumed nor exclusive. An illustration of these connections is shown in Fig. 2.

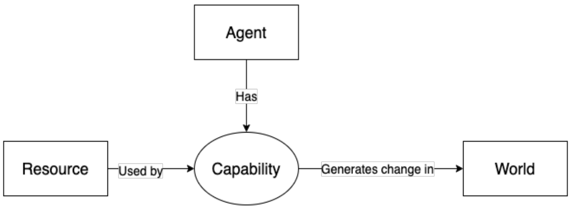

Fig. 2. Capability as a process that changes a state in the world object, using some resources (object)

The capability is associated with an *agent* system, which can be either a CS, a constellation, or the SoS as a whole. The agent needs to acquire its needed resources, and equipment is typically acquired when the CS is prepared for joining the SoS. This can for instance include equipping vehicles in the platooning SoS with short- and long-range communication equipment to allow them to communicate. For the Metropolitan Multi-Model Transport SoS, it entails installing communication equipment and passenger verification equipment

Consumables need to be re-supplied continuously to retain the CS capabilities. One example is energy supply to vehicles in a mobility SoS, where the vehicles need to plan their routes so that they pass gas or charging stations sufficiently often. A third resource type is information from other CS. Understanding the interactions between CS, mediators, and infrastructure when it comes to resource supply, and associated compensation such as payments, is fundamental in SoS analysis, especially in commercial applications.

A complex system usually has many capabilities that it can perform, sometimes simultaneously. However, the available resources may be required by several capabilities, which creates complex constraints on what can actually be achieved at the same time. This is particularly obvious in the SoS as a whole, where each capability is realized by a constellation. If a certain CS is uniquely required in several capabilities, it becomes a bottleneck that reduces what the SoS can do in parallel, and hence requires coordination and prioritization on the SoS level. This is particularly challenging in collaborative SoS, where there is no central decisionmaker.

V. SOS EXAMPLES

Throughout the paper, we provide examples of collaborative SoS from two problem domains, but where there are substantial differences: metropolitan multi-modal mobility, and truck highway platooning. In this section, those two examples are briefly introduced in more detail.

A. Metropolitan Multi-Modal Mobility

As illustrating example, we use a mobility SoS designed to operate in a Metropolitan setting in Sweden. The area of interest consists of a major city and its surroundings, including semi-rural areas where there is currently a perceived need for each household to own one, or more commonly more than one, cars. We are investigating how a collaborative SoS solution would be implemented in such an area. The users and stakeholders of the SoS give rise to different use cases that the SoS needs to be able to handle, for instance: commuting to work; child transports to schools; elderly people's subsidized travels; subsidized travel to non-time-critical health care appointments; health care personnel visits at home; shopping trips; deliveries of goods to stores and businesses; deliveries to homes; recreational and vocational transports. In Sweden, the responsibility for children's transport to schools and subsidized transport for elderly and functionally variated people rests with the local municipalities, while the responsibility for subsidized health-care transports lies at the regional level. Note that there are of course also other necessary transports, e.g., emergency services, ambulances, police. These are not included amongst the use cases.

The CS are in this case different means of transport. In our work on this scenario, we mostly assume autonomous vehicles of three different sizes: small, medium, large. Public transports in the form of buses, trains and trams are also included as CS. Recall that a mediator is an element of the SoS without independent purpose: it is created in order to facilitate the functioning of the SoS. There are three types of mediators in this scenario: a constellation formation service; a payment distribution service; and a travel needs service that is the interface to the user/traveller. Note that there can be several different competing instantiations of each of these mediators.

A constellation in this case is a set of vehicles that work together to solve a set of transport needs. Decisions that the CS need to make in this context include: where to go when empty (to maximise chance of receiving new assignment soon); whether to accept a proposed assignment or not; which route to take when on assignment (to optimize both fuel use, time to goal, and opportunity to get more passengers/cargo).

Mediators need to make decisions on routes and passenger assignments for CS, as well as which transport requests to prioritize. This entails that the mediator needs to solve a complex optimization problem, which is most likely difficult and requires decisions on which approximations to use."

B. *Truck Highway Platooning*

The second example is highway platooning for trucks, where the idea is that a lead vehicle, which is driven manually, is followed closely by several other vehicles using automated driving. The benefit is that aerodynamic drag can be substantially reduced by shortening the distance between the trucks, leading to lower energy consumption. However, there is also a cost in that trucks must wait for each other to form platoons, which can increase transportation time and lower the usage ratio of trucks. A platoon in this example corresponds to a constellation in the general terminology. It is in this case clearly seen that the constellation level is necessary to fully understand the dynamics of the SoS: all trucks whose operating organizations have joined the SoS will be CS. However, at a specific time, only a few of the trucks will belong to platoons/constellations. While a truck can only be in one platoon at a time, it is certainly possible for it to join several during its lifetime.

As was discussed in [11], the key operational decision is whether a truck should wait for another truck to form a platoon/constellation, or if it should continue on its own. This is an economical equation which balances the expected fuel saving against the cost for waiting, that results in a later arrival and a lower utilization of vehicles. Depending on what information the vehicle has available when making the decision, including positions and plans of other vehicles, it will make different decisions. The situation awareness is thus important and can have architectural consequences such as introducing mediating systems.

As always, the managerial decisions of joining the SoS at all, *i.e.,* to buy trucks equipped for platooning, are related to the operational decisions, and this has been studied in [12]. The overall effectiveness of the SoS is highly dependent on the number of CS that chooses to join, and the architecture as well as incentives may need to be adjusted to increase this number.

VI. DECISION-MAKING FOR A CS – JOIN OR LEAVE

It is the constellations that actually execute work in the SoS, and realize its capabilities by combining capabilities of its CS. Hence, it is the most important concept for discussing the need for SoS and it is important for a CS to be able to make decisions about when to join or leave a constellation. In a collaborative SoS, there is no controlling entity that instructs participants to collaborate. Instead, the decision is made independently by each individual CS. The decision could be made either entirely within the CS or after consultation with its operating and/or owning organization. In addition to using available data and requests from other CS, the decision must also be based on the goals and values of the CS, as explained in Section III.

The CS will in general have several goals. Some of these are general and common to all CS operated by the same organization. Others, also general, come from the owning organization. Finally, there are also goals that arise from within the CS itself – for instance by breaking down a high-level goal into a plan, where each step could be considered a goal. Different goals have different importance, which will also vary in time. Some goals are compatible, while some run counter to each other.

An important source of goals are commissions or assignments from customers. When a request for, *e.g.,* a transportation comes, CS that could solve parts of the need could add a goal to take part of solving it, and hence receive some payment for it. This is an inferred goal, which comes from the overarching goal of making money.

Another influence on the decision-making are rules and regulations. This comes both in the form of legislation from society (at national, regional, and municipal level) and as rules in different organizations. Such rules, too, have in principle an associated importance or, equivalently, an associated cost (fine) for breaking them.

A special kind of rules depend on the agreements which the operating organization has with the SoS and with other operating organizations. These could take the form of agreements never to leave a constellation without consent from all other participants, with an associated cost for breaking the agreement.

Collaboration opportunities arise when different CS can receive value from working together while still having the possibility to achieve their internal goals. The value received can take many forms, *e.g.,* direct monetary compensation from an external user; monetary compensation from another CS; savings in operating costs; goodwill, *i.e.,* the benefits gained from collaborating without receiving monetary compensation.

The collaboration opportunity is realized by joining a constellation. The constellation must be able to meet the needs of the users, *i.e.,* it must have the capability to perform the changes in states that the users request.

For a CS, choosing to join a constellation will have long-ranging implications. In platooning, joining a constellation means that it is not possible to join another. Before taking the decision, the CS must evaluate not only the benefits of joining but also determine what other platooning opportunities might arise in the future. These possible alternatives must then be evaluated and the one that gives the best return for the CS and its owning and operating organizations chosen.

In the Metropolitan Multi-Modal transport system, a CS must similarly evaluate the alternatives to joining a constellation. A constellation in this case corresponds to a set of vehicles that together solve the transport needs of one user. A vehicle/CS can thus be in several constellations at the same time. For instance, a vehicle that it scheduled to collect a schoolchild can during the same journey also transport a retiree to a health appointment. Optimizing for maximum desired effects in this SoS becomes a complicated optimization problem under uncertainty.

The decision to leave a constellation has similar characteristics as the join decision. The CS must evaluate the benefits of staying or leaving, taking account of both explicit penalties imposed by the SoS for un-cooperative behavior and the loss of reputation that will follow both the individual CS and the operating and owning organizations. Such decisions will likely require approval before they can be implemented by the CS.

In general, it will be impossible to find the optimum assignments of CS to constellations. Approximations will be necessary. When making these approximations, the different requirements on the transport system must be taken into account. This means that some transports will be more important than others. This must then be reflected either in the payment given to CS that participate in solving them or that other incentives must be given.

In Fig. 3 we show how CS decision-making is influenced by information from the world model of the CS as well as laws/rules and goals/values of owner and operator. In order to update the world model, it is necessary both to have own sensors and to be able to exchange information about the world with others. Thus, semantic interoperability between CS is important [13]. When deciding to join or leave a constellation, perhaps the most important factor will be the rules and doctrines that the operating organizations develop. These must be applicable to most cases and enable quick determination of whether to participate or not.

The benefit that a CS gets from a constellation will thus depend on which other CS participate. This can be modelled as a game where the utility depends on others' actions. Game theory is thus an essential ingredient in the decision-making process, as is situation awareness.

In all decision-making, the CS will need to consider whether to break or abide by the set of rules. Breaking a rule is associated with a cost but might nevertheless be worth it. For instance, in the Metropolitan Multi-Modal transport system, a vehicle that is scheduled to pick up a retiree for a health-care transport might decide to instead take on a more profitable transport. In other cases, a CS might not have the authority to break a rule of its own volition but could ask its operating organization for permission to do this. The operating and owning organizations can also use data from their CS to build a case for changing the rules.

Fig. 3 does not include societal goals explicitly. They are however present both in their influence on the goals of owners and operators and as codified into laws and rules. We distinguish between rules that are determined by the SoS itself, and laws that are set by the surrounding society. There are different time-scales and different processes for changing them.

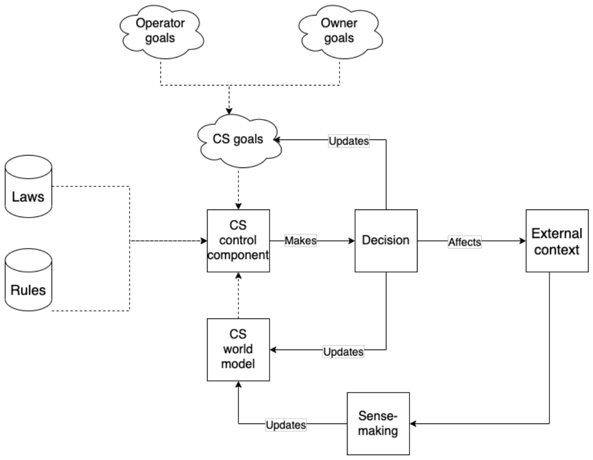

Fig. 3. Overview of information flows that affect the decision of a CS. Dotted arrows indicate influence flows from source to destination, e.g., the CS control component is influenced by the CS world model.

VII. RELATED WORK

The question of CS operational decision-making related to joining or leaving constellations relates to a broad range of subjects, some of which have already been mentioned above. An important characteristic of SoS is that the utility of each CS depends not only on its own choices but also on the actions of other CS. It can be assumed that this utility is decisive for the decisions a CS makes regarding whether it will join or leave the SoS or a specific constellation. This mutual dependency between the utilities of the CS is what creates the structural dynamics of the SoS, and it relates closely to a long tradition of research into game theory. It is only recently that researchers have started to explore the connection between SoS and game theory, and a systematic literature review of the topic is provided in [14]. The present paper extends previous research by providing insights into the structure of the games relevant to understanding CS operational decisions.

Another area which has recently gained interest in the SoS community, and particularly in defense applications, is Mission Engineering. A systematic literature mapping of how missions should be described concluded that the main elements are tasks, triggers, and constraints [15]. Based on this conceptual model, a language for modeling missions, based on the KAOS formalism, was proposed and exemplified using a flood monitoring example [16]. The Mission Thread Workshop was proposed as a method for analyzing end-to-end behavior of an SoS [17]. A workshop with key stakeholders is the main activity. Based on the resulting step-by-step description of the mission, important architectural concerns can be elicited. In [18], mission engineering is regarded as consisting of the three phases of acquisition, integration into an SoS architecture, and operations. These phases are detailed and illustrated through a border protection example. The results presented in this paper are also applicable to mission engineering but are more general. It is mostly in directed and acknowledged SoS that it makes sense to talk about common missions that are allocated to CS, whereas in collaborative SoS, the CS may have their own objectives but gain from sharing resources and information to conduct those missions more effectively.

Henshaw et al. [10] analyze eight different usages of the term “capability” by different stakeholder categories. They also use the analysis to relate capability engineering to systems engineering. An ontology for capability engineering is developed in [19], through a rigorous process involving several case studies from different sectors. Traditional systems engineering and capability engineering are compared in [20], concluding that capability engineering is needed to deal with the complexity of modern SoS. A three-dimensional set of views for capability engineering is provided by [21]. The first dimension is layers, which consists of integrated systems, SoS, and capability management. The second dimension is the lifecycle. The third dimension is operational capability elements, and it consists of people, process, equipment, and technology, infrastructure, and sustainment. An architecture for analysis of capability needs, assessment of capability options, and making choices about requirements is described in [22]. This and similar work on capability-based planning for the military domain can provide a fertile ground for further exploration of constellations in SoS.

An interesting paper is [23] which discusses the formation of a SoS and applies logical reasoning to determine what capabilities are needed in the SoS. The method given there could also be applied to the formation of constellations in directed SoS. For collaborative SoS, it is however necessary to have methods more based on optimization than logical reasoning, since the CS can choose to join or leave a constellation.

VIII. CONCLUSIONS AND FUTURE WORK

We discussed what a CS must take account of when making decisions, focusing on the decisions to join and leave a constellation (*i.e.,* actively collaborating with other CS in the SoS). Examples from two collaborative SoS with different characters were given. The need to take account not only of short-term gains but also others’ actions and the goals of owning and operating organizations was highlighted. Perhaps most importantly, since the gain for a CS will depend on the actions of others, there is a strong need for game theory and situation awareness in the CS control system.

We argue that it is necessary for the control element of a CS to understand not only the surrounding environment, but also to have models of others’ world models as well as of their probably future actions. It must be possible to predict whether other participants will uphold their parts of the collaboration or leave the constellation early. While such behavior could entail retaliation, as mentioned above, a CS that determines that the benefit of leaving the constellation (to, for instance, be able to join another, more high-paying one) outweighs the costs should nevertheless decide to leave.

In future work, we will further explore the connections between situation awareness, game theory and systems of systems, both at the CS/constellation level and for the Sos as a whole. The design and development of a SoS also entails many decisions and can in some sense be compared to forming a constellation.

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