01 Nov 2017

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Walter Barnes

Ya-nan Song

Rong-hua Xu

Cihan H. Dagli
Missouri University of Science and Technology, dagli@mst.edu

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/engman_syseng_facwork/419

Recommended Citation

W. Barnes et al., "Enabling Flexibility through Forming and Evolving Systems of Systems," *Procedia Computer Science*, vol. 114, pp. 19-27, Elsevier, Nov 2017.
The definitive version is available at https://doi.org/10.1016/j.procs.2017.09.059

Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 114 (2017) 19–27

Procedia Computer Science

www.elsevier.com/locate/procedia

Complex Adaptive Systems Conference with Theme: Engineering Cyber Physical Systems, CAS October 30 – November 1, 2017, Chicago, Illinois, USA

Enabling Flexibility through Forming and Evolving Systems of Systems

Walter L. Barnes II[a], Ya-nan Song[b], Rong-hua Xu[b], Cihan H. Dagli[a], Ruwen Qin[a]*

[a]*Department of Engineering Management and Systems Engineering, Missouri University of Science and Technology, 600 W. 14th Street, Rolla, Missouri, 65401, USA*

[b]*College of Automation, Guangdong University of Technology, Guangzhou, 510006, China*

Abstract

Flexibility is a highly desired attribute of many systems operating in changing or uncertain conditions. This paper presents a study of enabling flexibility through designing and operating systems of systems (SoSs). The paper analyzes flexibility mechanisms of SoSs and, accordingly, identifies needs for flexibility that SoSs can meet. Following that, it proposes a hierarchical network as a more flexible SoS architecture for complex or distributed large-scale systems. Then, decision problems for forming and evolving a SoS network are defined. A case that involves integrating distributed renewable energy sources with the main grid is presented to illustrate the implementation of the proposed methodology. Results from this study support the idea of acquiring and maintaining flexibility with SoSs. The paper also identifies research needs for advancing this particular use of SoSs.

Peer-review under responsibility of the scientific committee of the Complex Adaptive Systems Conference with Theme: Engineering Cyber Physical Systems.

Keywords: System of systems, flexibility; dynamics; microgrid; distributed energy sources

1. Introduction

Flexibility is a desired attribute of various systems operating in changing or uncertain conditions [1], [2]. Therefore, it has been an important consideration of system design and widely implemented in practice. For example, a production line may be designed to be flexible in switching among product models, or accommodating product

* Corresponding author. Tel.: +1-573-341-4493.
E-mail address: qinr@mst.edu

1877-0509 © 2017 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the Complex Adaptive Systems Conference with Theme: Engineering Cyber Physical Systems.
10.1016/j.procs.2017.09.059

updates, to respond to changes that may be unknown early in the lifecycle. Nowadays, systems are increasingly more complex or larger than they were used to be, to adapt to the growing and expanding social needs of human beings and rapid technological advancements. The complex architecture of those systems, and the growing importance of embedding flexibility to these systems, make the design and operations of flexible systems a research question for systems engineers.

What flexibility can be created through the design and operations of a system, and how, remain research questions. The current literature on flexibility is largely centered on specific application domains, such as manufacturing flexibility (e.g. [3], [4]), workforce flexibility (e.g. [5], [6]), and others. Despite many successful cases of creating flexibility in various domains, the literature has not been generalized enough to readily support the design and use of flexibility for any engineered systems that are growing in both types and complexity. Moreover, system performance is often characterized by multiple attributes, and flexibility is usually one attribute strongly interdependent of others. Flexibility induces increased or new interactions among systems or system components. Flexibility desired by a system or its elements usually does not naturally exist. The creation and use of the flexibility unavoidably affect other elements or need the collaboration of them. The actual contribution of flexibility to a system is a derivative in that the contribution depends on the evolution of underlying variables driving the needs for flexibility. All the features above make it important to calibrate the flexibility level during the design phase to ensure that the created flexibility is executable and will effectively produce the anticipated benefits later in operations.

This paper is motivated to analyze flexibility mechanisms of systems of systems (SoSs) to propose the adoption of a framework, or hierarchical network, for creating flexibility. The novelty in this paper is the derivation of a strategy for forming and evolving SoSs to provide needed flexibility. Specifically, the study is focused on changes or uncertainty that cannot be handled by a simple system in a cost-effective manner, but by systems of systems (SoSs) [7]. A SoS is a reconfigurable arrangement of independent and useful systems to deliver unique capabilities for a mission [8]. A capability is the ability to execute a specified course of action. It is unlikely the central mission can be accomplished by an individual system. We remark that a SoS is not designed to be a simple collection of systems that each brings one of the required capabilities to the SoS [9], [10]. Five characteristics of SoS distinguished a SoS from a system [11], [12], which are autonomy, belonging, connectivity, diversity, and emergence. The remainder of this paper is organized as the following. The next section briefly summarizes the relevant literature to acknowledge the status of current research. Then, Section 3 presents the proposed framework for enabling flexibility through designing and operating SoSs, followed by an illustrative case that demonstrates the rationale and feasibility of the proposed methodology in real-world applications. Important findings from this study and identified research needs are summarized at the end, in Section 5.

2. The Literature

Generally speaking, flexible systems are those that can make changes easily to cope with changes or uncertainty. While it is a desirable characteristic, flexibility is an ambiguous concept. Within the domain of systems engineering, three streams of research efforts have particularly tried to address this issue to improve the communication and capability of designing and analyzing flexible systems among systems engineering practitioners and academics. The first stream of efforts is about defining flexibility (e.g., [1], [2], [13], [14], [15]). These studies all emphasized the critical aspects of flexibility including the existence of needs for flexibility, flexibility mechanisms, and effects of flexibility. The second stream has been focused on measuring and quantifying flexibility (e.g., [14], [16], [17], [18]). The degree to which changes can be made to a system's architecture is a way of quantifying flexibility [16], [19], [20]. Metrics for flexibility have been developed based on system's architecture and used to measure the flexibility of generic system architectures [20]. The third stream studied the interdependence of flexibility with other attributes of systems (e.g., [16], [21], [22]), and the impact of flexibility on system capabilities, performance, and others (e.g., [2], [13], [16]). All these efforts have built a foundation for the study in this paper.

A few research papers explicitly studied the flexibility of SoSs. Gorod et al. [23] examined the flexibility of a SoS as the flexibility of autonomy, flexibility of belongs, flexibility of connectivity, flexibility of emergency, and flexibility of diversity. They developed a concept of flexibility dynamic in their study. Recently, Dagli, et al. [24] led a series of research for developing flexible and intelligent learning architectures for SoSs.

Different than the literature, the work of this paper is focused on analyzing the flexibility mechanisms of SoS and, accordingly, deriving a strategy for forming and evolving SoSs to provide needed flexibility.

3. The SoS Framework for Flexibility

Flexibility is valuable to stakeholders who not only face changes or uncertainty but are sensitive to these. With appropriate flexibility the stakeholders are able to make changes quickly and easily to effectively meet their needs despite of the uncertainty. Among all identified needs for flexibility, some can be met by forming and evolving SoSs.

3.1. Flexibility Mechanisms of SoSs

To create flexibility through forming SoSs, we first need to determine flexibility mechanisms of SoSs. A SoS is an arrangement of independently operated and managed systems, which are integrated into a larger system that delivers unique capabilities. A SoS, as well as each of its constituent systems, consists of parts and relationship, and a whole of these is greater than the parts [8]. Flexibility can be acquired using one or a combination of the following flexibility mechanisms.

- **Flexibility of SoS type**: There are four SoS types ([9], [25]), which are directed SoS, collaborative SoS, acknowledged SoS, and virtual SoS. A SoS may be designed to be able to switch from one SoS type to another, and it makes the SoS more adaptive to a wider range of operating conditions.
- **Flexibility of SoS configuration**: A SoS is usually reconfigurable in terms of selecting constituent systems to participate in the SoS, as well as determining the collaboration among selected constituent systems, in a dynamic manner.
- **Flexibility of constituent systems**: Constituent systems that are flexible in the capabilities to provide to the SoS, as well as in the performance of providing the capabilities, provide another degree of flexibility to the SoS.[26]

The three mechanisms above form a foundation for designing SoSs for the purpose of enabling flexibility.

3.2. The Needs for Flexibility

SoSs would generally meet the needs for flexibility that fall into the following categories.

- **Changes or uncertainty in constituent systems**: Constituent systems' willingness to participate in the SoS, as well as their participating performances, may change over time for many reasons. New systems may emerge, becoming better choices for the SoS than existing constituent systems. Most of the time these changes are unpredictable.
- **Moving or ambiguous SoS objectives**: The specified outcomes, or objectives, of SoS may evolve for different reasons, such as changing requirements or behavior of stakeholders, dynamic operating environments for the SoS, and others.

All the needs for flexibility are caused by dynamics of various aspects, including operations, technology, market, environment, human behavior and perception, resources, and others. Facing the dynamics, either the optimum of a SoS is transient or SoS objectives are a moving target. A SoS can be quickly and easily revised, reconfigured, and re-calibrated, to always fulfill the SoS central mission.

3.3. Hierarchical Network: a More Flexible SoS Architecture

A single SoS may not be able to meet all the needs for flexibility. Hierarchical SoS network is a more flexible SoS architecture that is able to adapt to complex and widely distributed large-scale systems. We categorize hierarchical SoS networks into two major types, which are discussed in the following.

- **Network of SoSs**: Forming a single SoS on a wide area might not be the best design. Instead, a network of multiple SoSs that are geographically distributed may be a better choice. These SoSs are homogeneous in that they are designed to fulfill the same central mission. They are also heterogeneous because each is specifically formed to serve a local group of stakeholders. These SoSs are locally optimal, but maybe not on the entire range of area. Connecting spatially distributed SoSs as a network allows them to collaborate with each other to move towards the global optimum, better serving all stakeholders over a wider area. Since its components are SoSs, this network inherits the properties of SoS.
- **Super SoS**: Some constituent systems of a super SoS are heterogeneous SoSs. This architecture is appropriate when the bigger system needs heterogeneous capabilities that some are impossible to be delivered by simple systems but SoSs.

3.4. Decisions for Forming and Evolving a Flexible SoS

Flexibility provides choices to stakeholders facing changes or uncertainty. They dynamically make choices to respond to changed conditions reactively or potential changes proactively. To best use the flexibility they have, agents of SoSs make the following decisions.

- **SoS architecting**: This involves selecting an SoS configuration to create or evolve to, which can be represented by a graph with N selected constituent systems or SoSs and K edges among them, $G(N, K)$, in fulfilling the SoS mission. Choices of SoS architectures are discrete.
- **Operational planning and execution**: If some or all of the selected constituent systems are flexible, the SoS agent needs to determine what capacities to request from the flexible constituent systems, the specifications of participation and collaboration for them. The deviation of real contributions from the specifications needs to be managed in a near real-time manner.
- **Collaboration approach**: When needed, the approach to coordinating constituent systems in the SoS can be switched from one to another. A SoS with a dedicated agent coordinating constituent systems may be switched to one relying on peer collaboration.

The decisions discussed above are interdependent. For example, the SoS architecting uses the inputs from operational planning and execution; meanwhile, the result from the former constrains the latter.

4. A CASE STUDY: INTEGRATED MICROGRIDS AS AN SOS NETWORK

Renewable energy sources (RESs) are often geographically distributed, volatile, and intermittent. Using a single RES or a conventional source usually does not meet requirements on energy generation and supply, such as affordability, reliability, sustainability, efficiency and others. The distributed nature of RESs suggests an evolutionary change of the central energy generation, transmission, and distribution. Distributed energy sources and the main grid are not competitors but complements. In this paper, we describe how a network of SoS can be designed to integrate spatially distributed stochastic RESs with the main grid.

4.1. A Microgrid as an SoS

Microgrids (MGs) have become an effective solution for utilizing distributed RESs. A MG is a localized group of power sources and loads, which can operate both in a stand-alone mode or a grid-connected mode of operations. Fig. 1 illustrates a MG with RESs. This MG in a stand-alone mode includes heterogeneous energy generators such as photovoltaic (PV) systems, wind turbines (WT), and diesel engine (DE) generators; energy storage devices such as battery systems; and loads. When different generation sources and storage devices collaborate with each other, becoming a bigger system, the energy supply of the system is more reliable, safe, and cost-effective than that with a single energy source. This concept may seem counterintuitive due to the intermittency of RESs, but renewable energy actually can be effectively utilized when multiple generators are connected and supported by energy storage systems [27], [28]. As applied to renewable energy, the Law of Large Numbers dictates that the combined output of every PV, WT, and DE connected to the grid is far less volatile than the output of a single RES [27], [28]. The way they operate and collaborate can be controlled to evolve over time to better meet stochastic local loads. When connected with other MGs and the main grid, this MG can support or be supported by them.

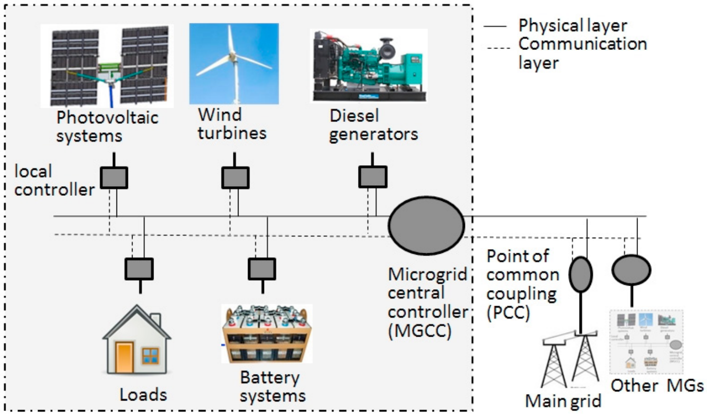

Fig. 1. A microgrid with renewable energy sources

- **The SoS framework**

  A MG can be seen as a SoS [29], [30], [31]. A MG is an integration of heterogeneous and independently operated and managed systems (power generators, storage devices, and the main grid if under the grid-connected mode), for generating and supplying energy to meet load demand. The MG is flexible because many aspects of the MG can be dynamically adjusted, including the connection and disconnection of existing or newly developed constituent systems, the way in which the selected constituent systems collaborate, and the operations of these systems. The integration of distributed generation and storage devices as a SoS provides greater ability to meet load demand than a simple system does.

- **A bi-level network**

  Connectivity is an important characteristic of SoS. Fig. 1 shows that constituent systems of the MG are connected as a two-layer network. At the physical level it is a power network wherein the power flows from supplies (generation and/or storage devices) to demands (local loads, charging storage devices, and loads from the main grid and other MGs). At the communication level it is an information network responsible for system monitoring, information collection, data exchange, and transferring control signals. Each generation or storage device is connected to the network by a device controller and, similarly, a load is connected to the network by a load controller. All these controllers are named local controllers (LCs) shown in Fig. 1.

- **SoS type switches**

  Coordinating constituent systems of a SoS is critical to the delivery of expected outcomes. The microgrid central controller (MGCC) of an MG is designed for this purpose, particularly under the stand-alone mode. It controls the MG in terms of assessing the operating status of MG, forecasting and planning power generations, dispatching power to loads, and managing load demand. MGCC communicates with the local controllers of the MG. When the MG is connecting to the main grid or other MGs, its MGCC also communicates with these external systems through a distribution management system (DMS). There are multiple control methods for coordinating elements of MGs [30]. The control method for an MG determines the SoS type of it.

- <u>Central hierarchical control - directed SoS</u>: When a central hierarchical control method is used, the MG can be a directed SoS in that it is built and centrally managed during long-term operations to fulfill specific purposes. The constituent systems maintain an ability to operate independently, but their normal operational mode is subordinated to the central managed purpose. In a central hierarchical control, LCs follow and execute the orders of MGCC, but they may still have certain degree of autonomy or intelligence.

- Decentralized hierarchical control - acknowledged SoS: When a decentralized hierarchical control method is used, the MG is more likely to be an acknowledged SoS. An acknowledged SoS has its objectives, independent management, and resources for the SoS; however, the component systems are also independently operated and managed in that they retain their independent objectives, sources, and development and sustainment approaches. Changes in the constituent systems are based on collaborations between the SoS and the systems. In a decentralized hierarchical control, LCs demonstrate a higher degree of autonomy and they optimize the control of the local devices. The MGCC attempts to influence the local optimization. The optimality of decisions by MCGG and LCs in this control method is sensitive to the system reliability and the communication speed, particularly in geographically distributed large-scale SoSs. Implementing the decentralized hierarchical control currently can still be technically challenging.
- Decentralized control – collaborative or virtual SoS: When a decentralized control method is chosen, the MG is a collaborative or virtual SoS whose constituent systems interact more or less voluntarily to fulfill agreed upon central purposes. Compared to the decentralized hierarchical control method above, this distributed control lacks a dedicated central controller like the MGCC to coordinate local devices. LCs are responsible for optimizing the operations of distributed devices. LCs have no or limited communicate with each other and operate mainly based on local measurements.

A MG may operate in various conditions so that a single coordination method may not always be the best. A change in the operating condition or the central mission may require a switch of the MG operating mode. Consequently, the coordination method, and therefore the SoS type, of the MG may be changed too. For example, when a MG switches from the grid-connected operating mode to the stand-alone mode, the control method of the MG may be changed temporarily from a central control to a decentralized control. This triggers a change in the SoS type. To obtain the flexibility of using multiple coordination methods, the communication network for exchanging information and transmitting control signals needs to be well designed to adapt to any coordination methods.

4.2. Connected MGs and the Main Grid as an SoS Network

While an MG can be independently managed and operated to coordinate the RESs and loads locally, it can be connected to other MGs and/or the main grid to exchange energy. The full value of RESs requires the grid connection [33]. Connecting multiple MGs and the main grid as a SoS network adds additional flexibility, which helps achieve greater performance than the additive outcomes of unconnected individual energy systems. That is, an additional utility is added by forming a SoS network.

This paper uses an example in [34] to illustrate the SoS network, which is composed of two MGs (MG_A and MG_B) and the main grid (MnG). Fig. 2 illustrates the eight configurations of the SoS network. The network can be seen as a graph with three nodes. The eight configurations are different from one to another in terms of the number edges connecting nodes. The flexibility at the SoS network level lies in the possibility of intendedly switching from one configuration to another, for adapting to different operating conditions. There are 24 possible intended switches because only one edge can be added or removed at one time. There are unintended switches too, mainly occurring during unplanned outages of the main grid. For example, configuration II may be switched to configuration VII due to an outage of the main grid.

Generally speaking, a SoS network with N different MGs and the main grid has $2^{(N+1)N/2}$ configurations in total. Each configuration can be intendedly switched to one of another $(N+1)N/2$ configurations if only one edge can be changed at one time. Therefore, in total there are $2^{(N+1)N/2}$ $(N+1)N/2$ intended switches between configurations.

Similarly, there are different methods for coordinating constituent SoSs in the network, and so the type of the SoS network may be revised if the control method is changed. A MG network in configuration II and coordinated by a central hierarchical control method may be switched to configuration VII unintendedly due to the outage of the main grid. The control method may be switched to the distributed control temporarily, and so the SoS type of the network becomes a collaborative SoS. The configuration switch and the control method switch need to be coordinated carefully to avoid negative impacts [34].

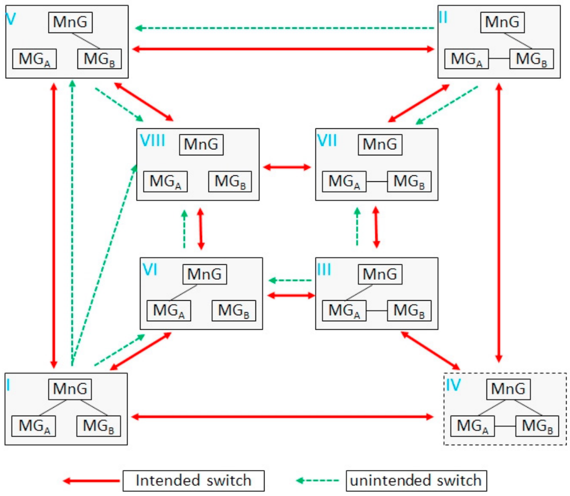

Fig. 2. Configurations of a SoS network

4.3. Evolution of MGs and MG Network

A SoS or SoS network usually evolve over time, driven by the dynamics discussed in Section 3.2 and determined by the decisions described in Section 3.4. In the following we describe these decisions in this case study, which usually fall into the category of energy management.

- **Generation planning of individual MGs**: Given the forecasts of local loads and RESs of an MG *N* periods of time into the future, as well as energy exchange requests from other MGs and the main grid, the MG agent plans the power generation of each source, the charge or discharge amount of each storage device, and the energy exchange commitments to other MGs and the main grid.
- **Power dispatch of individual MGs**: The actual loads and RESs are measured every period of time. Given the measurements (e.g., wind speed, solar irradiance), as well as the energy exchange commitments to other MGs and the main grid, the SoS agent adjusts the power outputs of individual generation sources and the charge/discharge amount of storage devices to optimize the power flows and stabilize system voltages.
- **Planning and coordination of power exchanges:** The power exchange, either between different MGs or between a MG and the main grid, aims to generate additional utility at the SoS network level by mitigating the unbalanced generation and load demand on a wide area.

If communication capability is provided, the three types of decisions can be made in an integrated manner in that they are interdependent. The first two decisions, which are coordinated by the MGCC and LCs of each MG, are more closely coupled. They can be modeled as a two-stage stochastic programming problem, a robust optimization problem, or a rolling optimization problem. Generally speaking, the third decision is a game-theoretic problem and coordinated by the DMS. The way in which the third decision is integrated with the first two depends on the type of the SoS network.

5. Conclusion

In this paper we proposed a methodology for acquiring and maintaining flexibility for distributed large-scale or complex systems in changing or uncertain conditions through forming and evolving SoSs. Findings from the preliminary study of this topic positively support the proposed methodology.

Challenges present in the implementation of the proposed methodology. From the management perspective, SoSs have multiple flexibility mechanisms. Decisions for forming SoSs and involving them over time are complex; in that the decisions are interdependent and across multiple time scales. From the technology perspective, the executions of SoS reconfiguration, system performance re-calibration, and SoS type change, require advanced control technologies. Addressing these challenges need a seamless collaboration between systems engineers and domain experts.

Acknowledgements

The work of Drs. Ya-nan Song and Rong-hua Xu is supported by the Science and technology Projects of Guangdong Providence of China 2014A020217015 and 2016A020222012.

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