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The Federated Satellite Systems paradigm: Concept and business case evaluation

Alessandro Golkar [a,b,*], Ignasi Lluch i Cruz [a,1]

[a] Skolkovo Institute of Science and Technology, 100 Novaya Ulitsa, Skolkovo, Russia
[b] Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, United States

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ABSTRACT

This paper defines the paradigm of Federated Satellite Systems (FSS) as a novel distributed space systems architecture. FSS are networks of spacecraft trading previously inefficiently allocated and unused resources such as downlink bandwidth, storage, processing power, and instrument time. FSS holds the promise to enhance cost-effectiveness, performance and reliability of existing and future space missions, by networking different missions and effectively creating a pool of resources to exchange between participants in the federation. This paper introduces and describes the FSS paradigm, and develops an approach integrating mission analysis and economic assessments to evaluate the feasibility of the business case of FSS. The approach is demonstrated on a case study on opportunities enabled by FSS to enhance space exploration programs, with particular reference to the International Space Station. The application of the proposed methodology shows that the FSS concept is potentially able to create large commercial markets of in-space resources, by providing the technical platform to offer the opportunity for spacecraft to share or make use of unused resources within their orbital neighborhood. It is shown how the concept is beneficial to satellite operators, space agencies, and other stakeholders of the space industry to more flexibly interoperate space systems as a portfolio of assets, allowing unprecedented collaboration among heterogeneous types of missions.

1. Introduction

The last five decades have seen important breakthroughs in the field of Information Technology (IT). Together with the miniaturization and integration of electronics, one of the most prominent features of the field is the networking approach adopted by IT developers, which allows harnessing the full potential of computers by connecting and operating them in networks, creating virtual, flexible cloud infrastructures [1] and emerging capabilities transparent to hardware. Nowadays, the global implementation of this concept is the Internet, used worldwide and indispensable to billions of people around the globe. Nevertheless, the field has not reached its full potential, with the Internet of Things (IoT) concept [2] promising to be the next revolution in the way we generate and manage information about the world. The ideas about distribution, virtualization and scalability behind these successful technical breakthroughs have been spread to other domains, notably electric power distribution systems in the form of smart grids [3]. These ideas have not, to the date, been adopted nor extensively discussed by Space mission designers, operators nor scholars.

Drawing from ideas in cloud computing and changes already underway in other fields, in this paper we propose the Federated Satellite Systems (FSS) paradigm. Likewise to

* Corresponding author. Tel.: +7 919 969 4221.
E-mail addresses: a.golkar@skoltech.ru (A. Golkar), ignasi.lluchicruz@skolkovotech.ru (I. Lluch i Cruz).
[1] +7 495 280 1481.

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cloud computing nodes, FSS consists in spacecraft networks trading previously inefficiently allocated and unused resource commodities such as downlink bandwidth, storage, processing power, and instrument time. FSS hold the promise to enhance cost-effectiveness, performance and reliability of existing and future space missions, by networking different missions and effectively creating a pool of resources to exchange between participants in the federation. This exchange improves the overall welfare of the federation by improving overall cost efficiency or by creating business opportunities, implementing usage-based pricing policies in the network. FSS envisions a space-based resources market, where missions dynamically offer to the federation any underutilized capabilities such as bandwidth, processing power or data storage, and access to such resources depending on their needs. FSS are a new space mission paradigm, aiming to switch from independent, isolated space missions to a highly dynamic, constantly evolving in-orbit infrastructure capable of supporting different missions and even deploying software-based, virtual missions. FSS constitute the dawn of cloud computing environments in space, which will significantly change the way space missions are conceived and operated.

This paper introduces and describes the FSS paradigm, and develops an approach integrating mission analysis and economic assessments to evaluate the feasibility of the business case of FSS. The approach is demonstrated on a case study on opportunities enabled by FSS to enhance space exploration programs sustainability, with particular reference to the International Space Station (ISS). In previous papers [4,5], we introduce and analyze some of the key technical aspects for the implementation of FSS, and identify the major challenges for technological development required for the development of satellite federations in space.

The remainder of this paper is structured as follows. Section 2 provides background to FSS, and provides context through a literature review. Section 3 describes in more detail the idea of FSS, providing definitions that will be used throughout the paper and describing a market assessment exercise to demonstrate the opportunities enabled by FSS. Section 4 illustrates the proposed federation idea illustrating a case study in Earth Observation. Building on this example Section 5 presents a structured approach for the evaluation of the business case of a satellite federation and describes a second case study on the implementation of federations in space exploration. Section 6 summarizes the results achieved by this paper, and draws conclusions from the research.

2. Background

FSS can be considered as a new instance of distributed satellite systems [6,7]. Distributed systems have already been implemented in space as satellite constellations. Typical space constellations feature identical type of spacecraft designed to carry out the same tasks, whose aggregation support the primary mission goal pursued by the constellation [8]. The idea behind distributed systems is to allocate mission functionality to multiple elements, as means to enable new functionality (such as space-based geo-localization [9]), to mitigate programmatic constraints or risks (such as the case of NASA's 3-element Mars Sample Return campaign [10]), or to reduce the size of the required space platforms (like fractionated spacecraft elements deployed on service areas) [11].

FSS are composed of heterogeneous spacecraft, with different goals and capabilities. The technical developments needed for networking heterogeneous missions have recently been explored in [12], and in [13] as ways to enhance CubeSat capabilities. FSS envision opportunistic collaboration across spacecraft, much alike what is done in peer to peer networks [14] and in cloud computing [1]. The ideas of the space internet [15,16], solar system internetworks [17], and sensor webs [18] can be considered as precursors to the idea of satellite federations. All these are system concepts that make use of spacecraft interoperability to enable their functions, allocated within spacecraft operated by a single set of stakeholders (a space agency, or a nation). Several space agencies around the globe started investigating interoperability for different aspects of space missions, including the establishment of a Consultative Committee for Space Data Systems (CCSDS) [19] for data product standard development and ground segment interoperability, and the IOAG Space Internetworking Strategy Group (SISG) for the development of the concept of Solar System Internetwork [20]. Researchers started looking at disruption-tolerant protocols as means to enable these novel space network concepts in distributed satellite systems [21]. Interoperability within spacecraft components has also been of interest to the community, with standards such as SpaceWire developed for this purpose [22]. Yet, all the above-mentioned concepts lack of a vision of the establishment of a commercial market of on-orbit resources, which this paper intends to propose as a contribution to the state of the art.

One of the notable research efforts in this direction was DARPA's F6 program, exploring the concept of Fractionated Spacecraft [23]. This advanced system concept disaggregates and reallocates the functionality of a spacecraft into multiple smaller units, networked and operating together to achieve mission objectives. Despite the ambitious goals of F6, the program was terminated in early 2013 due to a cut in funding from the sponsoring agency [24]. Instead of allocating mission functionality to smaller units, FSS attempts to establish a peer-to-peer network for the opportunistic sharing of resources among participant spacecraft. Table 1 illustrates the different distributed mission types discussed in this section. Fig. 1 shows a graphical representation of the differences between constellations, FSS and Fractionated Systems in their autonomy and mission goals dimensions.

The peer-to-peer network concept proposed by FSS could be extended to spacecraft anywhere to the solar system, converging with the interplanetary data relay system of systems proposed by NASA with SCaN [25]. Space-based networks have been implemented and extensively discussed [26–28] to achieve a variety of mission goals not only limited to deep-space communications, but most notably terrestrial mobile communications [29]. The space network concept enabling the deployment of FSS differs from the former by supporting ad-hoc, opportunistic links between heterogeneous