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Systems-of-Systems Taxonomy: Space and Airborne Systems Perspective

John D. Nguyen

Abstract

This chapter discusses the taxonomy of Systems-of-Systems (SOS) with a focus on space and airborne systems perspective. A discussion with a broad view of taxonomy with considerations for space and airborne systems classification, including SOS and Family-of-Systems (FOS), will be presented. The chapter defines taxonomic categories considering dimensions in the classification of space and airborne SOS based on their acquisition strategy, operational mode, and problem domain. Commercial and military acquisition strategies will be addressed along with their intentional operational modes and problem domains. The space and airborne systems discussed will be Satellite Communication (SATCOM) systems, sensing and imaging satellite systems and Positioning-Navigation-and-Timing (PNT) satellite, and military and commercial aircraft systems. The chapter provides examples on notional military SATCOM and manned aircraft systems.

Keywords: space systems, systems-of-systems (SOS), satellite communication, sensing and imaging satellite, positioning-navigation-and-timing (PNT) satellite, family of system (FOS), SOS engineering, constituent systems, acquisition, autonomy of constituents, application domains, standards, operational Independence, managerial Independence, evolutionary development

1. Background and introduction

The term "Taxonomy" used in this chapter will be borrowed from the definitions presented in Refs. [1–3], but with an emphasis on space and airborne perspective. This chapter defines taxonomy as a hierarchical structure framework to classify space and airborne systems terms into parent-and-child relationships, where each level of a hierarchy can be referred to as a "Category." In this chapter, "Systems" will be categorized as Systems of Systems (SOS) and Family of Systems (FOS). For general military space systems, military space FOS can be categorized as (i) Satellite Communication (SATCOM) systems, (ii) Sensing and Imaging satellite systems, and (iii) Positioning-Navigation-and-Timing (PNT) satellites. Practically, civilian space FOS can be categorized as (i) commercial FOS of Broadcasting satellites, (ii) commercial FOS of Wideband Internet satellites, and (iii) commercial FOS of Data, Video, Audio Communications satellites. In general, commercial space FOS can be categorized as (i) NASA FOS of Near-Earth Missions, (ii) NASA FOS Deep Space missions, and (iii) NOAA FOS Earth Surveillance satellites. SOS can be a

selected group of FOS that are connected together. For space systems, they (SOS) can be categorized as military, civilian and commercial space systems. For airborne systems, they can be categorized as military and commercial airborne systems, since civilian and commercial airborne systems are practically identical. In general, airborne systems can be categorized as (i) military manned aircraft systems, and (ii) military un-manned aircraft systems. Similarly, for commercial aircraft, it is also can be categorized as (i) commercial manned aircraft systems, and (ii) commercial un-manned aircraft systems. **Figure 1** presents our view of taxonomy for "systems". **Figure 2(a)** and **(b)** illustrate taxonomies for Space and Airborne FOS, respectively.

This chapter will focus on SOS taxonomy for space and airborne systems. Due to the constraint on the length, this chapter will only provide two taxonomy examples on space and airborne systems, where a generic space and airborne systems' taxonomies will be presented. For airborne systems, the example will be focused on manned airborne systems. The chapter is organized as follows:

   i. Section 2 describes existing SOS taxonomy framework described in [3];

   ii. Section 3 discusses our proposed SOS taxonomy framework for space systems;

   iii. Section 4 proposes an approach for SOS taxonomy framework for airborne systems;

   iv. Section 5 provides examples on notional military SATCOM and manned aircraft systems;

   v. Section 6 concludes the chapter with remarks on the taxonomy's needs for future space systems.
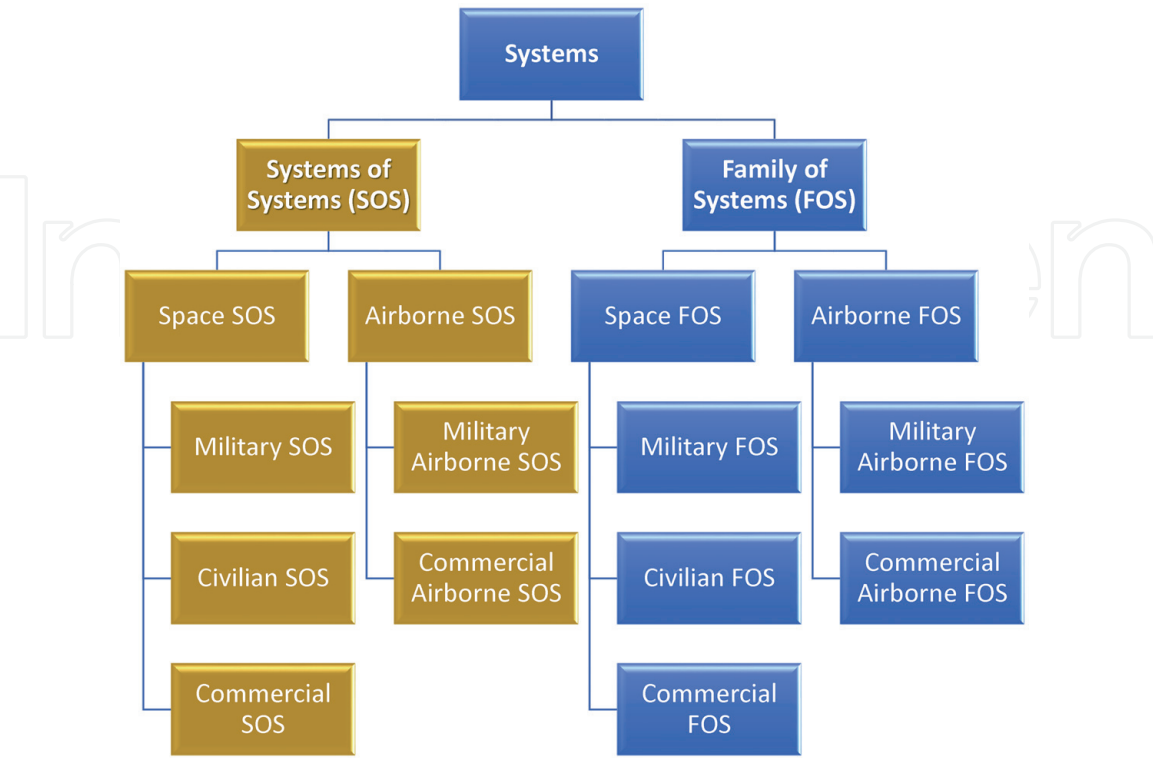
Figure 1.
A taxonomy definition of systems.
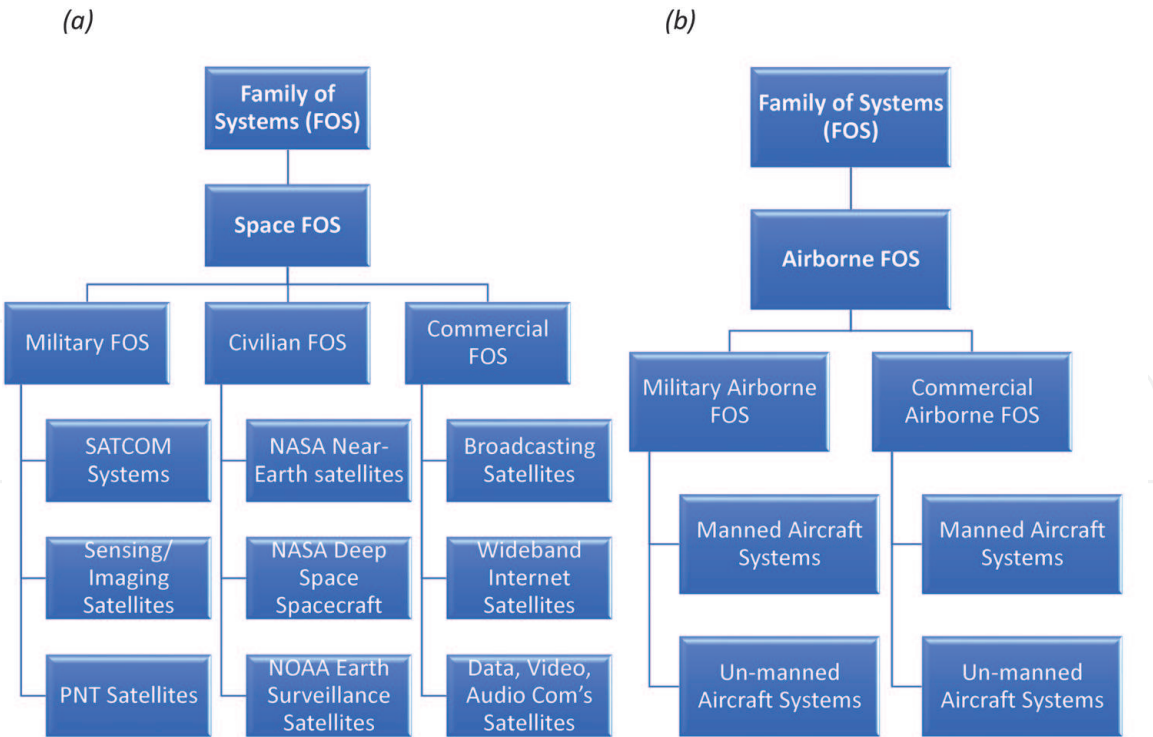
Figure 2.
Taxonomy definitions of space and airborne FOS (a) a taxonomy definition of space FOS (b) a taxonomy definition of airborne FOS.

2. Description of existing SOS taxonomy framework

This section describes a current perspective on the SOS taxonomy framework, where SOS can be categorized as three types:

- Acquisition type

- Operation type

- Domain type.

Each of the type will be classified into different component as shown in **Figure 3**. The following provides a summary of the three types and their associated components.

- **Acquisition type:** SOS is classified based on how the systems acquired [3]:

  o **Dedicated SOS:** Is defined as planned SOS, where they are consciously designed and engineered from the beginning to be SOS, where the interaction between the component systems is expected when the systems are acquired. As pointed out in [3], in the past, many military SOS were not acquired in this manner, and the emerging trend is to design military systems around the SOS concept.

  o **Virtual SOS:** Unlike dedicated SOS, this type of SOS is un-planned when the component systems are engineered and acquired. Another characteristic of these systems is that once their use has ended the
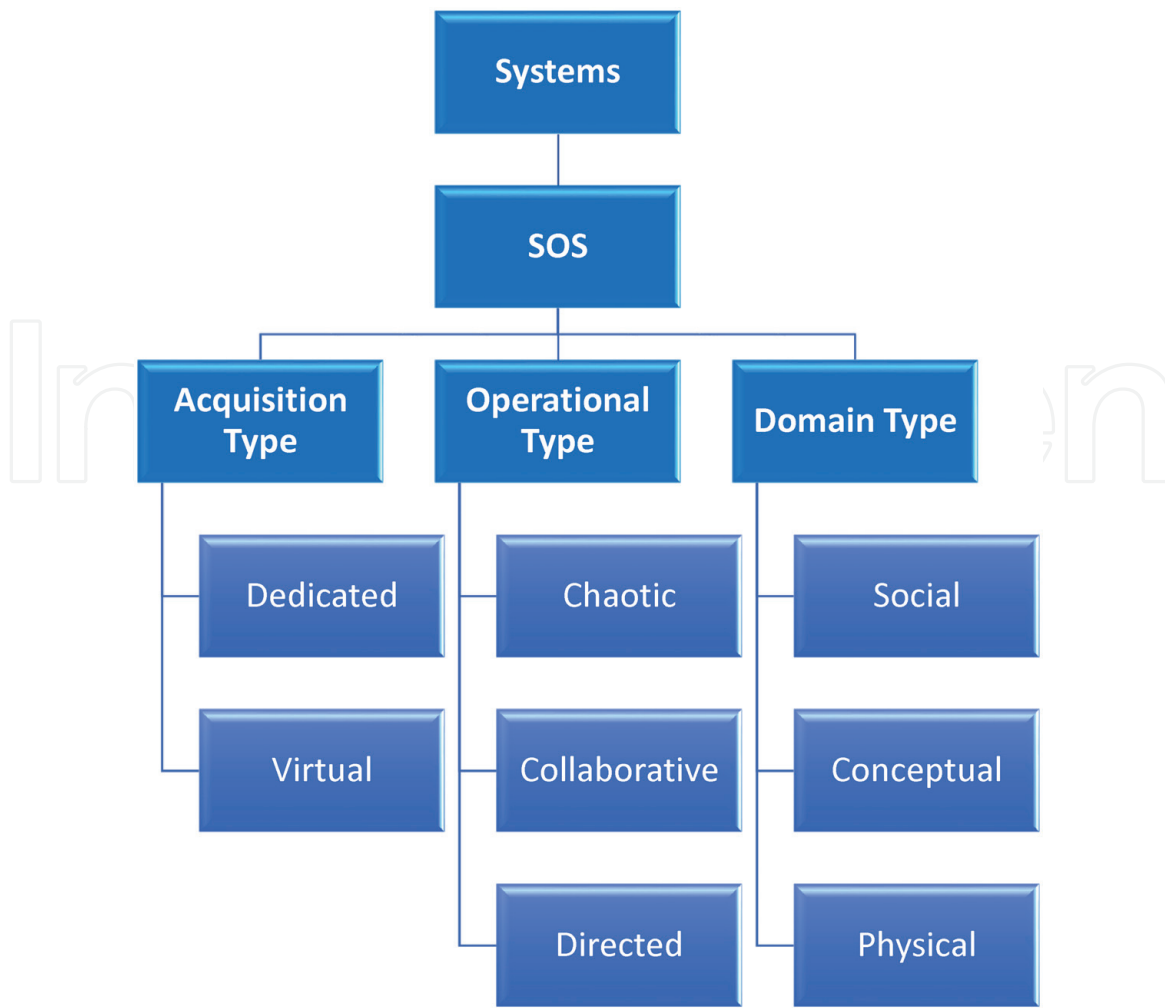
Figure 3.
Current SOS taxonomy framework [3].

component systems are usually disassembled and no longer operate as a part of a larger SOS.

- **Operational type:** SOS is classified based on how the systems operate [3]:

  ○ **Chaotic SOS:** This type of SOS has no central control authority or managerial entity and thus no agreed upon purpose.

  ○ **Collaborative SOS:** For this type of SOS, the component systems interact voluntarily almost out of necessity. Control and management authority have little power to coerce the behavior of the component systems. Control and Management authorities may issue standard practices and procedures by which components must operate to be a part of the larger system, but ultimately it is up to the component systems to acquiesce to those standards to become part of the larger system (as with the Internet). The overall behavior of these systems may still be somewhat unpredictable.

  ○ **Directed SOS:** This type of SOS is designed to have its control by a central management authority. The systems are designed and operated for a specific purpose.

- **Domain type:** SOS is classified based on how the domain that systems operate [3]:

○ **Social SOS:** Is defined as SOS that are either physical or conceptual SOS classes. As pointed out in [3], a social SOS is government.

○ **Conceptual SOS:** These systems do not exist as tangible entities in physical space nor do they operate on or manipulate matter. Systems that are conceptual include those in which humans interact with concepts or those that require no human intervention at all.

○ **Physical SOS:** These systems are operating in or on the physical world. These systems involve interactions between humans and the physical world or systems that are completely embedded in the physical world with no human interaction. These systems are composed of component systems that are tangible or affect matter.

3. Proposed SOS taxonomy framework for space systems

Figure 4 describes the proposed SOS taxonomy for space systems, where SOS can be categorized as military SOS, civilian SOS and commercial SOS. As discussed in Section 1, military SOS can be classified SATCOM SOS, Image/Sensor SOS, PNT SOS, and mixed SATCOM + Image/Sensor + PNT SOS. Similarly, the classifications for civilian and commercial SOS are also shown in **Figure 4**.

Each type of the military SOS (e.g., SATCOM SOS) can be further classified in terms of acquisition type, operational type and domain type. Using the current framework described in the above section [3], this section derives the proposed taxonomy framework for space systems. The section is organized as follows: (i) Section 3.1 presents a taxonomy framework for military space systems,
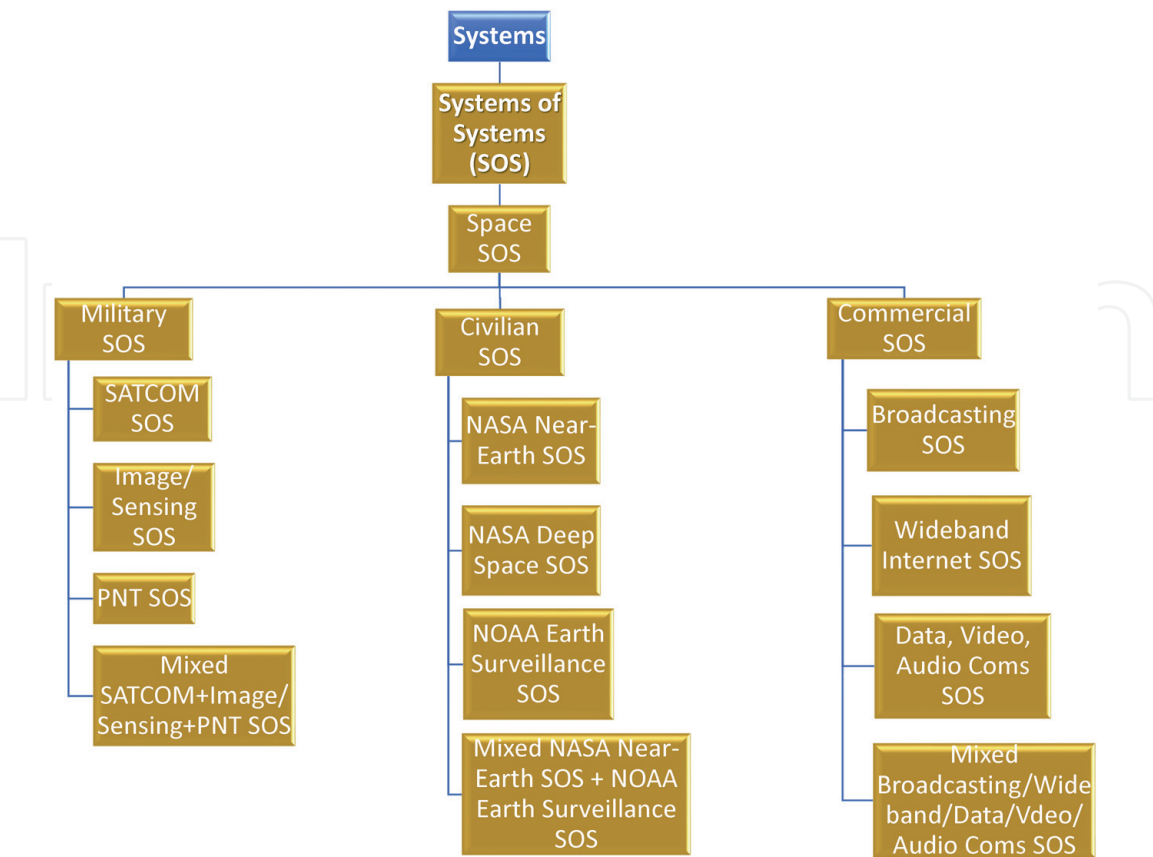
Figure 4.
Proposed SOS taxonomy framework for space systems.

(ii) Section 3.2 addresses the commercial space systems, and (iii) Section 3.3 discusses the taxonomy framework for civilian spaces systems.

3.1 SOS taxonomy framework for military space systems

Figure 5 presents our proposed SOS taxonomy for military space systems. The SOS taxonomy framework for military space systems can be categorized as:

- Acquisition type

    o Dedicated SOS

    o Virtual SOS

- Operation type

    o Collaborative SOS

    o Directed SOS
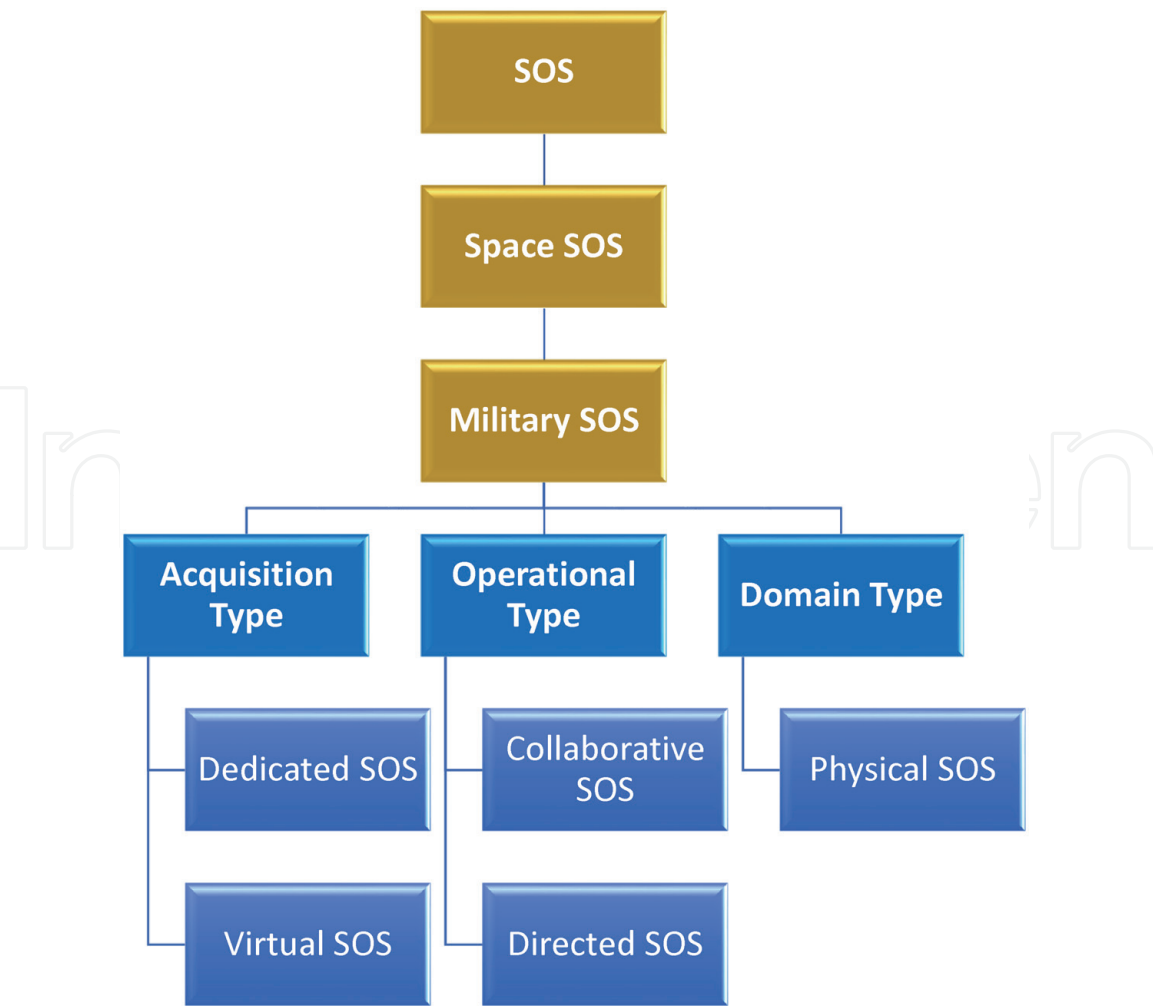
- Domain type:

    o Physical SOS

Figure 5.
Proposed SOS taxonomy framework for military space systems.

3.2 SOS taxonomy framework for commercial space systems

Figure 6 presents our proposed SOS taxonomy for commercial space systems. The SOS taxonomy framework for commercial space systems can be categorized as:

- Acquisition type

  - Dedicated SOS

- Operation type

  - Collaborative SOS

  - Directed SOS

- Domain type

  - Physical SOS

Note that the commercial framework missed a component in the acquisition type, namely, virtual SOS. This is because the SOS solution is usually derived from customer's needs. While for military space systems, due to the threats dynamic, the warfighter needs are changing at a fast pace and there will be un-planned SOS components to be deployed.
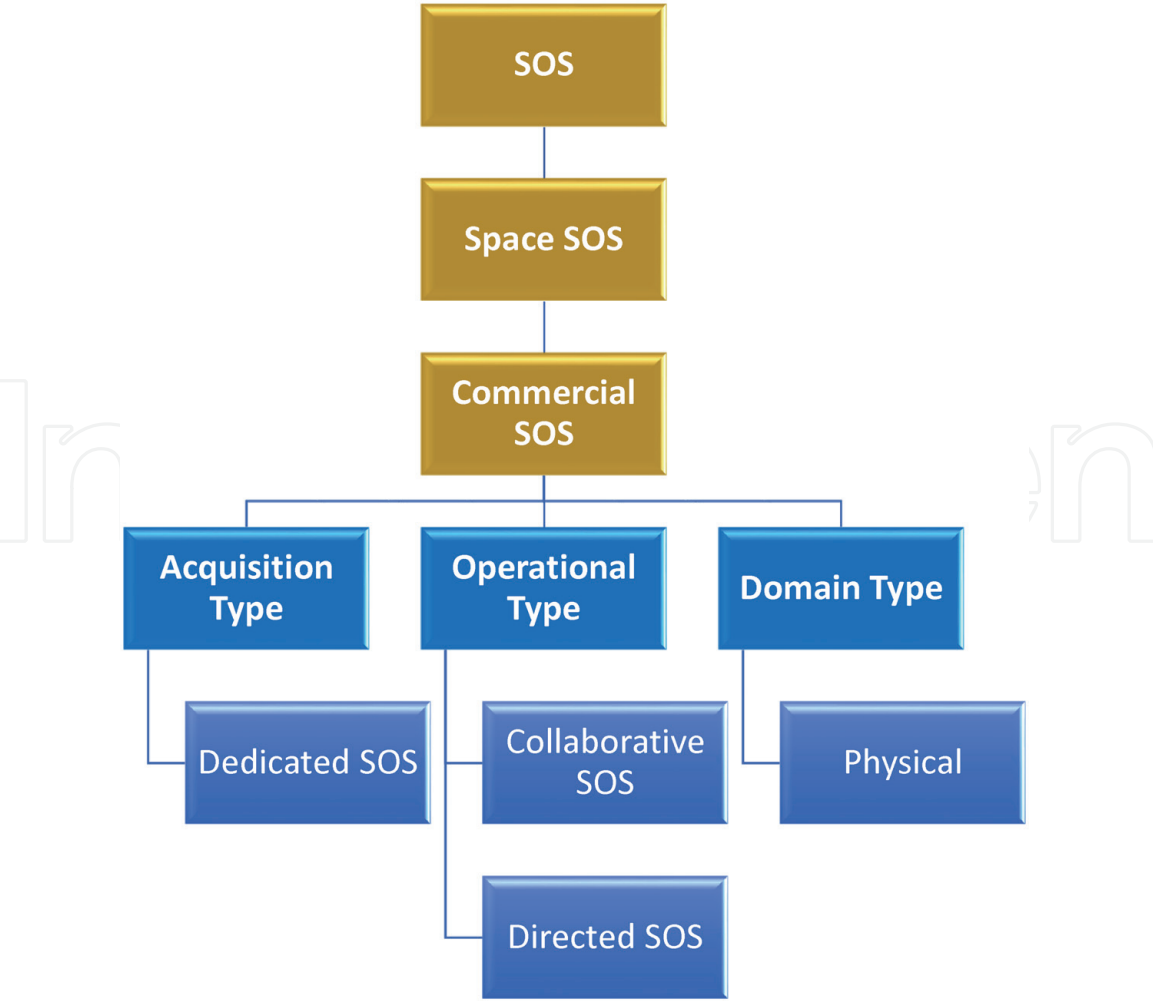

Figure 6.
Proposed SOS taxonomy framework for commercial space systems.

3.3 SOS taxonomy framework for civilian space systems

Figure 6 presents our proposed SOS taxonomy for commercial space systems. The SOS taxonomy framework for civilian space systems can be categorized as:

- Acquisition type
  - Dedicated SOS
- Operation type
  - Collaborative SOS
  - Directed SOS
- Domain type
  - Physical SOS

Note the proposed SOS taxonomy framework for civilian space systems is identical to commercial space systems, see **Figure 7**. Similar to commercial space systems, the SOS acquisition for civilian space systems is depending on a planned mission's needs.
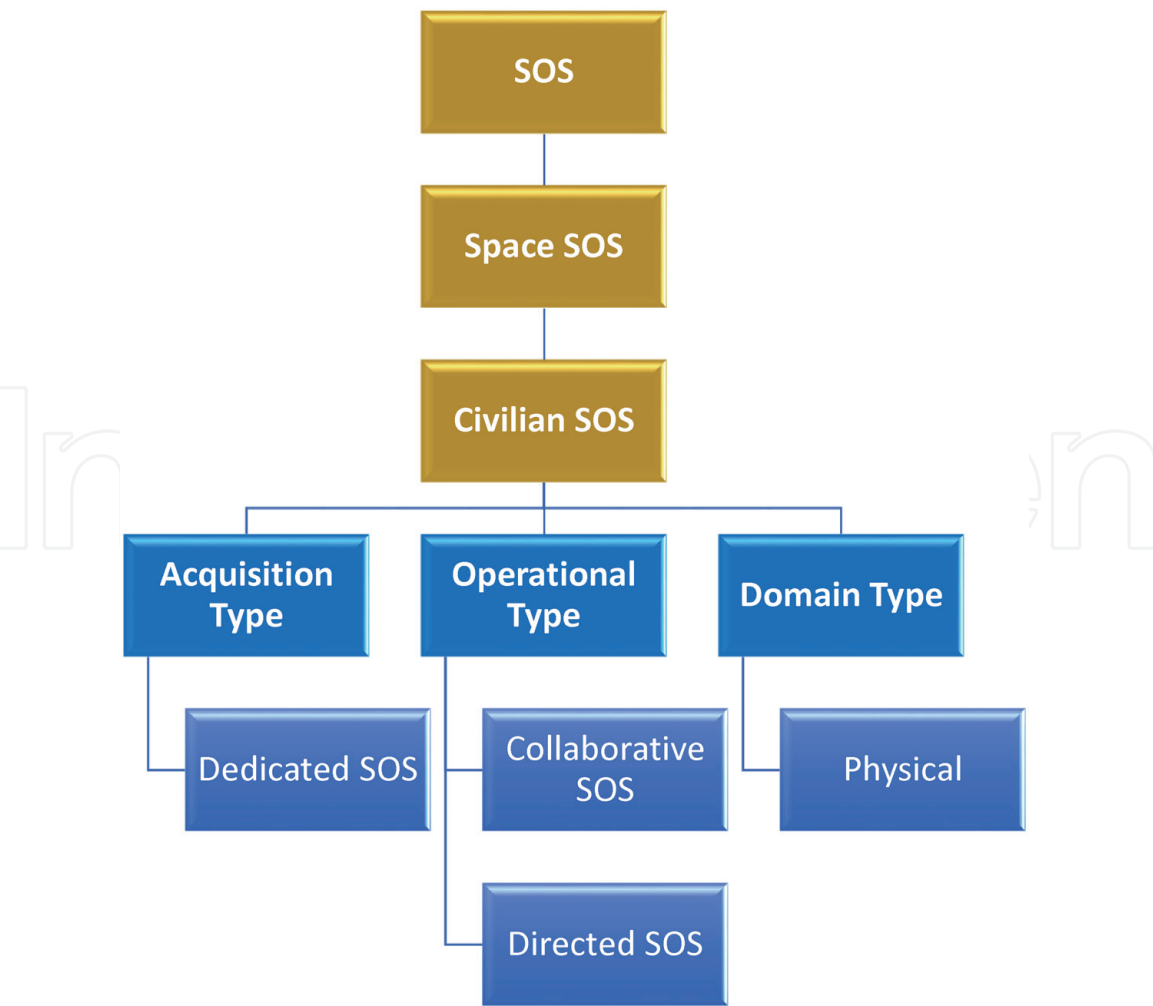

Figure 7.
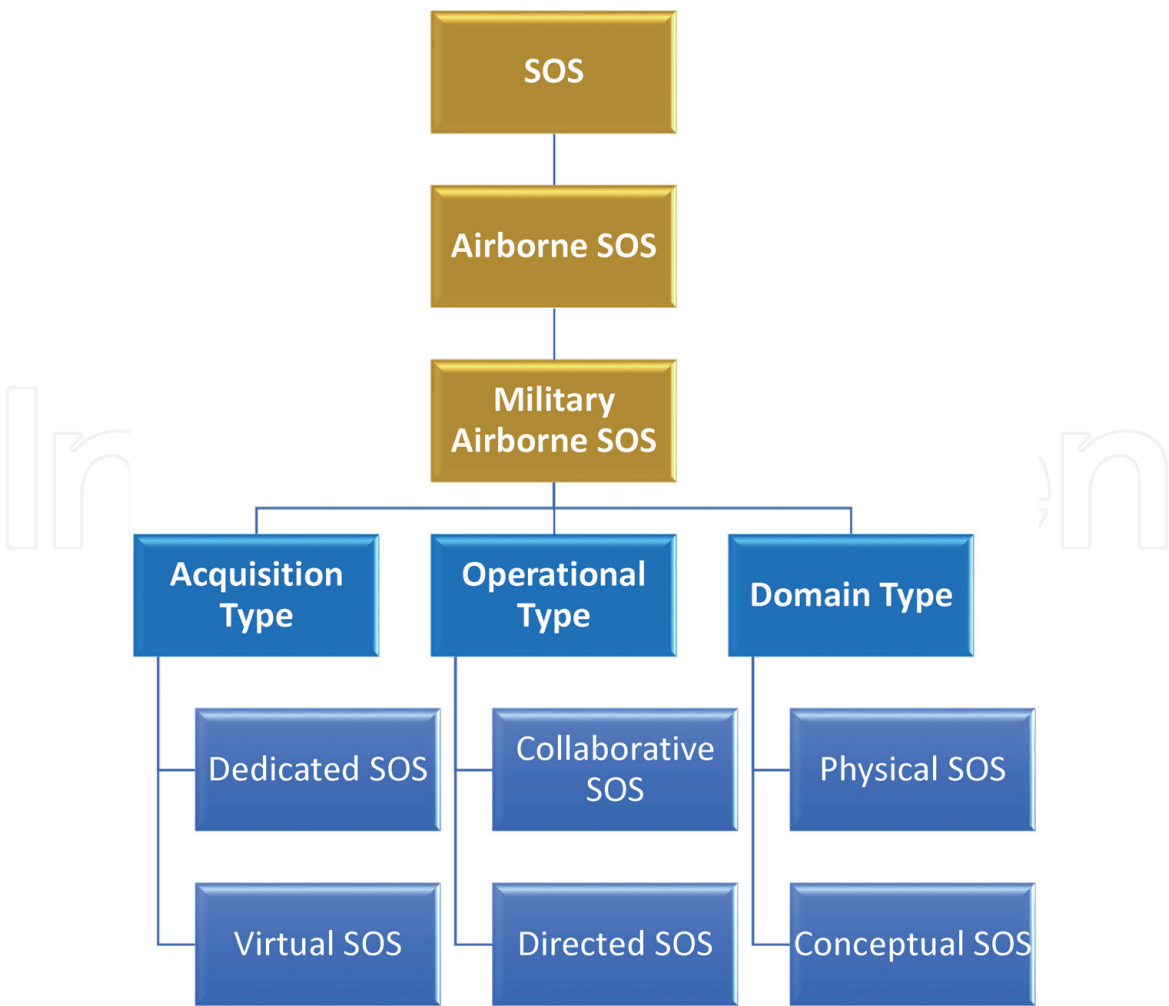*Proposed SOS taxonomy framework for civilian space systems.*

4. Proposed SOS taxonomy framework for airborne systems

Again, using the framework described in Section 2, this section derives the proposed taxonomy framework for airborne systems. The section is organized as follows: (i) Section 4.1 presents a taxonomy framework for military airborne systems, and (ii) Section 4.2 addresses the commercial space systems. Note that the taxonomy framework for civilian airborne systems is identical to commercial systems.

4.1 SOS taxonomy framework for military airborne systems

Figure 8 presents our proposed SOS taxonomy for military airborne systems. The SOS taxonomy framework for military airborne systems can be categorized as:

- Acquisition type

    ○ Dedicated SOS

    ○ Virtual SOS

- Operation type

    ○ Collaborative SOS

Figure 8.
Proposed SOS taxonomy framework for military airborne systems.

        ∘ Directed SOS

   • Domain type

        • Physical SOS

        • Conceptual SOS

Similar to military space systems, due to the threats dynamic, the warfighter needs are changing at a fast pace and there will be un-planned SOS components to be deployed in airborne platforms. However, there is an addition component that is included in the domain type, namely, conceptual SOS. For airborne systems, this conceptual SOS component provide pilot training systems that have components existed in both physical and non-physical domains. For the physical domain, the pilot training system includes the training facility. For the non-physical domain, the pilot training system includes the cyber space component, where the pilots encounter the non-physical entities for training purposes.

4.2 SOS taxonomy framework for commercial airborne systems

The SOS taxonomy framework for commercial airborne systems is very similar to the military airborne systems, except that the SOS component for acquiring un-planned systems is no longer required. Thus, the framework includes:
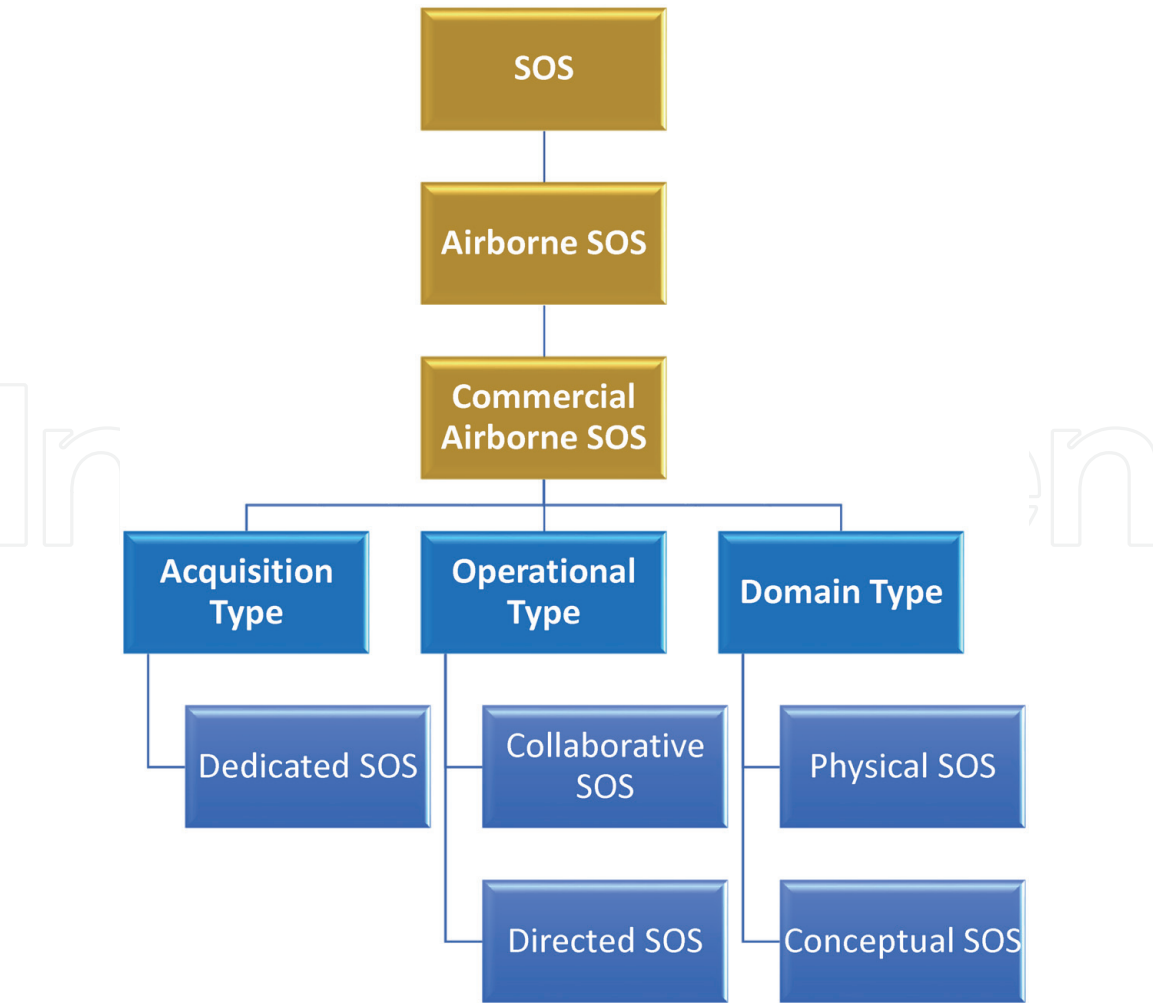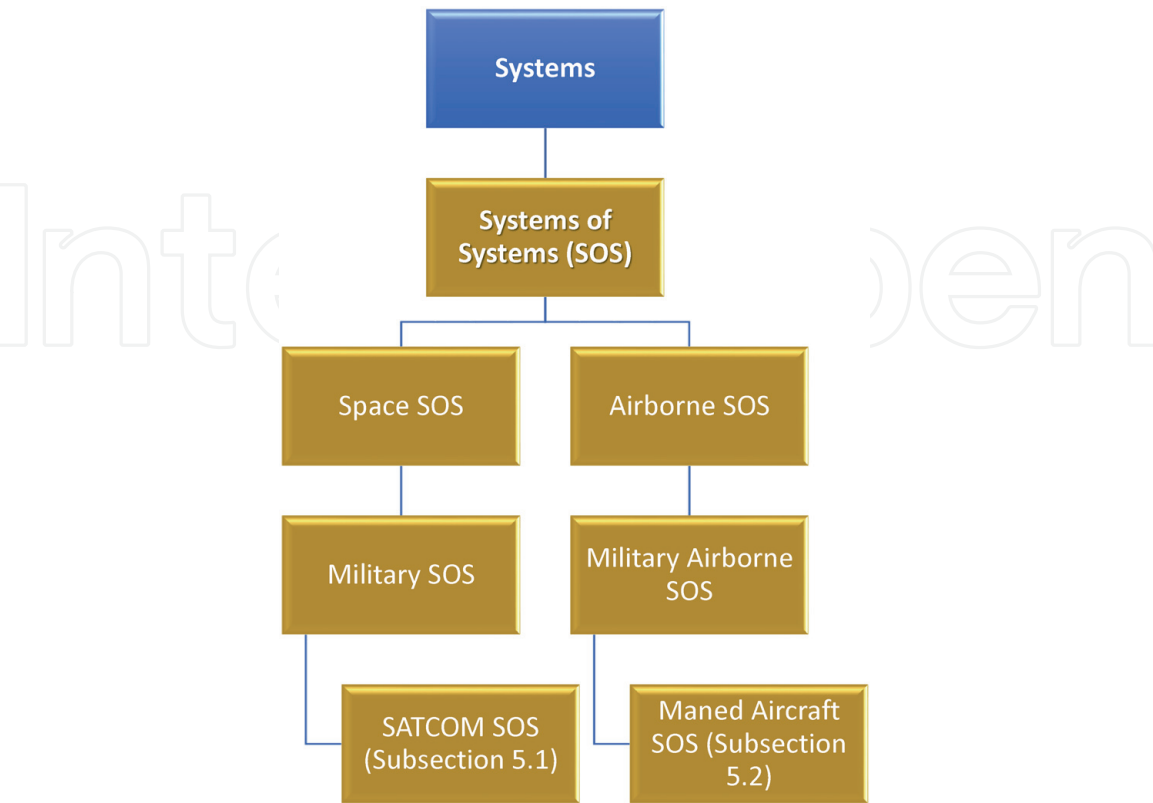

Figure 9.
Proposed SOS taxonomy framework for commercial airborne systems.

- Acquisition type

    ◦ Dedicated SOS

- Operation type

    ◦ Collaborative SOS

    ◦ Directed SOS

- Domain type

    ◦ Physical SOS

    ◦ Conceptual SOS

Figure 9 depicts the proposed SOS taxonomy framework for commercial airborne systems.

5. Examples on notional military space and airborne systems

This section provides examples of taxonomy on notional military space and airborne systems since the case for civilian and commercial systems can also be derived directly from these examples. **Figure 10** illustrates the two examples to be described in the following subsections. Subsection 5.1 presents an example of a taxonomy framework for a typical military SATCOM SOS. Subsection 5.2 provides an example of a taxonomy framework for a typical manned military aircraft that

Figure 10.
SOS taxonomy framework for military space and airborne systems (described in the following subsections).

can be used for the derivation of a taxonomy framework for un-manned military aircraft.

5.1 A notional military SATCOM system

A typical military SATCOM system with a fully process SATCOM payload can be classified into the following subsystem components that are part of a SOS design [4]:

- Received Antenna Subsystem (RX-AS)

- RF Front-End Subsystem (RF-FES)

- Fully Digital Processing Subsystem (FDPS)

- Tracking-Telemetry & Commanding Subsystem (TT&CS)

- Frequency & Timing Subsystem (FTS)

- Altitude & Control Subsystem (A&CS)

- Communication Security Subsystem (COMSECS)

- RF Back-End Subsystem (RF-BES)

- Transmit Antenna Subsystem (TX-AS)

Followings are the decomposition of each of the above subsystems. Typical RX and TX antenna subsystems include the following components [4]:

- Antenna Configurations

- Beamformer Component

- Antenna Controller Component.

Typical RF Front-/Back-End Subsystems include the following components [4]:

- Front-end

    o Low Noise Antenna (LNA)

    o Multi-wideband Receiver

    o Down RF Converter

    o Tunable IF Converter

- Back-end

    o High Power Amplifier (HPA)

    o Up RF Converter

The FDPS is the heart of a fully processing payload, and a typical FDPS includes the following components [4]:

- Analog-to-Digital Converter/Digital-to-Analog Converter (ADC/DAC)

- Digital Processor (e.g., Field Programmable Gate Array (FPGA))

- Modulator/Demodulator (MOD/DEMOD)

- Decoder/Encoder

- Digital Network Switch (DNS)

- Fully On-Board Satellite System Controller (FOBSSC)

A typical TT&CS includes the following components [4]:

- On-Board Ranging Processor

- On-Board Command Processor

- On-Board Telemetry Processor

Using a typical fully process SATCOM payload described above, **Figure 11** provides a SOS taxonomy framework for a notional military SATCOM system operating in an SOS environment.

5.2 A notional military airborne system

A typical military manned airborne system can be classified into the following subsystem components that are part of a SOS design [5]:
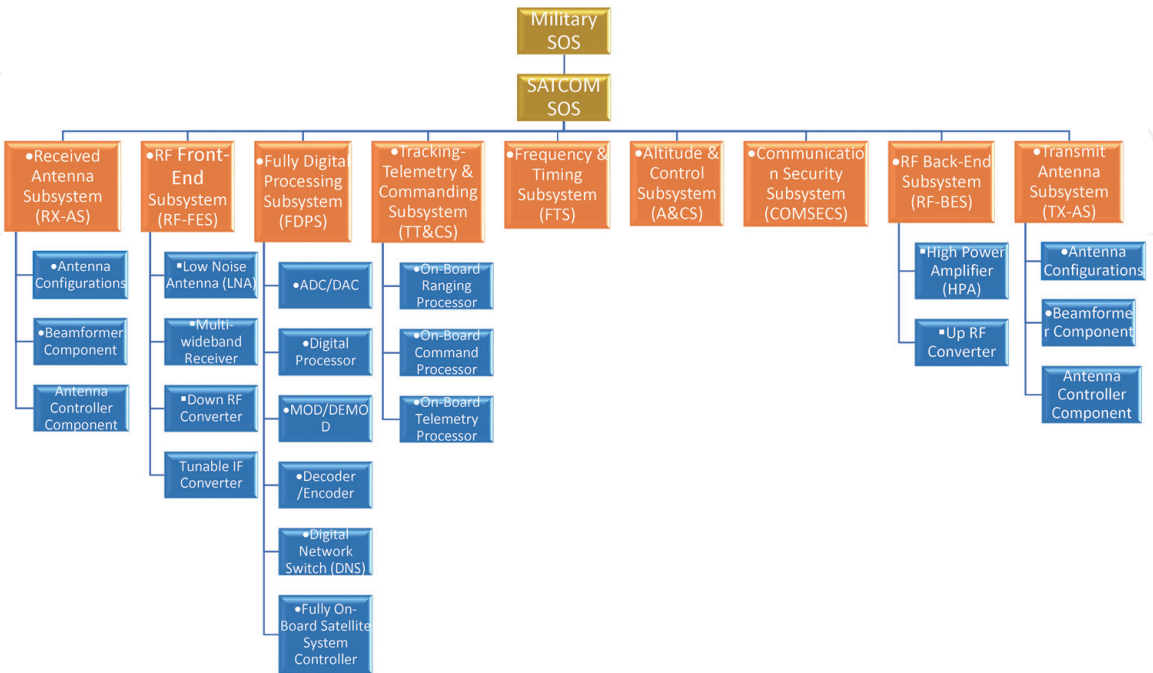
Figure 11.
SOS taxonomy framework for military SATCOM systems.

- Airframe

- Propulsion

- Application Software

- Communications / Friend-or-Foe (FoF) Identification

- Navigation / Guidance Control

- Central Computer
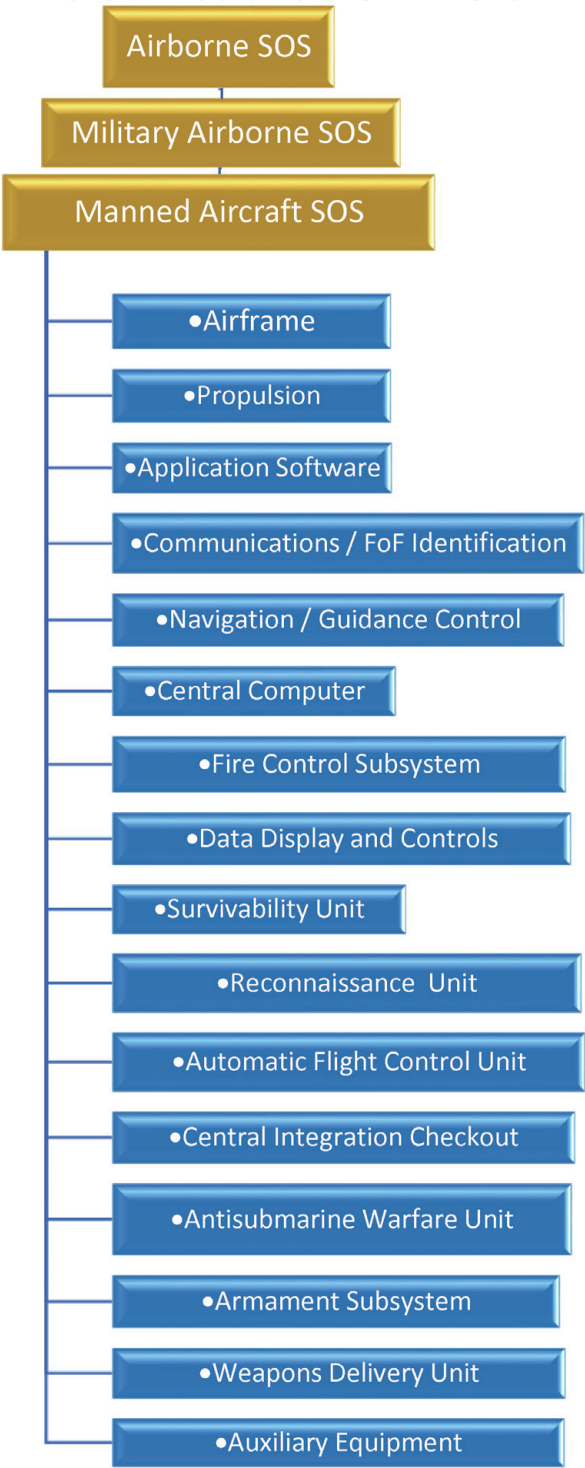
Figure 12.
SOS taxonomy framework for military manned aircraft.

- Fire Control Subsystem

- Data Display and Controls

- Survivability Unit

- Reconnaissance Unit

- Automatic Flight Control Unit

- Central Integration Checkout

- Antisubmarine Warfare Unit

- Armament Subsystem

- Weapons Delivery Unit

- Auxiliary Equipment

Figure 12 provides a SOS taxonomy framework for a notional military manned airborne system operating in an SOS environment.

6. Conclusion

This chapter provides descriptions of SOS taxonomy frameworks for space and airborne systems. A broad view of taxonomy frameworks with considerations for space and airborne SOS and FOS were presented. Using existing SOS taxonomy framework, the chapter proposed SOS taxonomy frameworks for space and airborne systems based on their acquisition types, operational modes, and problem domains. Examples on SOS taxonomy were provided for notional military SATCOM and manned aircraft systems. Similarly, examples for manned airborne and other space systems can also be derived by tailoring the framework presented in Section 5.

Conflict of interest

Notes/Thanks/Other declarations

Author details

John D. Nguyen[1,2]

1 John DTN Consulting Services, Huntington Beach, California, USA

2 Gulfstream Corporation, Long Beach, California, USA

*Address all correspondence to: johndncva@gmail.com

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