System-of-Systems Challenges and Considerations for Space Applications

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Introduction

- Why system-of-systems challenges and considerations in space applications
  - To put things in proper context, it is necessary to emphasize the word "system". There are various definitions of the word "system"
  - "A system is a group of interacting or interrelated elements that act according to a set of rules to form a unified whole[1]
  - Every aspect of the human condition adheres to some fundamental rules of a specific system type: engineering, biological, social.
  - The need to integrate domains is a key aspect of the development process of complex technologies to enhance the human condition, either terrestrial or space environment.
  - This paper is going to ponder on the challenges and possible considerations to develop SoS for space applications:
    - ✓ Elicit fundamental high-level questions that could provide better understanding of the challenges.
    - ✓ Facilitate consideration of appropriate methodologies and approaches. To leverage knowledge from terrestrial complex SoS.

Definitions

- There is a need to understand some basic definitions of a "system" and a "system-of-system" is.
- The International Council On Systems Engineering (INCOSE) has developed an extensive and authoritative body of work on this topics. The INCOSE definition of system and SoS will be referenced in the context of this paper. The INCOSE definitions are provided below.
- Definition of System
  - A system is an integrated set of elements, subsystems and assemblies that accomplish a defined objective. The elements that make up a system include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support system[2]. [2]fellows-initiative-on-system-and-se-definitions.pdf (incose.org)
- Definition of System-of-Systems
  - A system-of-systems (SoS) is a collection of independent systems, integrated into a larger system that delivers unique capabilities. The independent constituent systems collaborate to produce global behavior that they cannot produce alone[3]. [3]Systems of Systems Primer (incose.org)

The Case for System-of-Systems -1

- System-of-systems as stated in the definition, exhibit some key characteristics that differentiate it from a system.
  - Independence: Each system in a SoS is expected to exhibit autonomy and functionality; nevertheless, collaborating with other systems to achieve common goal.
  - Interconnectivity: In a SoS, systems are connected utilizing communication and information exchange mechanisms to achieve collaboration and coordination.
  - Emergent Behavior: The complete interactions between the systems in a SoS can lead to unpredictable emergent properties or behaviors that cannot be ascertained by examining individual systems.
  - Complexity: SoS is inherently complex due to the large scale of systems interconnectivity, diverse stakeholders and dynamic operating environments.
  - Dynamic Nature: Each constituent system evolves independently; responding to changes in requirements, technologies and environmental conditions.
  - Distributed Control: SoS does not exhibit centralized authority; consequently, control and decision making is typically distributed amongst the constituent systems.

The Case for System-of-Systems -2

- Challenges abound in SoS due to the complexity, interoperability, and emergent behaviors.
- Development and management of SoS require special methodologies and approaches
- SoS will proliferate in technology development and usage; considering the interdisciplinary nature of systems applicable for human endeavors in all domains: engineering, biology, social, environment, etc.
- These challenges extends to space application as humans think about having permanent settlements in space and other planets.
- However, the expertise acquired in current terrestrial SoS may not be adequate in the development of SoS for human habitation in space environment.

System-of-Systems Context and Literature Review-1

- This paper will focus on three key system domains: Engineering, Biological and Social. These system domains impact the human condition in all aspects of life experience.
- Their impact will be even more profound in the quest for human habitation in space. Hence, the interest to have closer examination of SoS in the context of these three domains.
- "The integration of biology and spacefaring has led to the development of three interrelated fields: Astrobiology, Bioastronautics, and Space Bioprocess Engineering" (A. Berliner et al, January 2024).

System-of-Systems Context and Literature Review-2

- Deployment of SoS of any domain is daunting. Space environment will be most unforgiven, considering the many obstacles: manufacturing, interfacing, scaling, deploying, updating, servicing, technology insertion, etc.
- Many on-going studies and research has provided better understanding of the challenges, overcoming many obstacles. However, there are still many unknowns in scaling the engineering, biological and social domains for space colonization.
- "We seek to solve 5 unsolved problems in space: Providing gravity, food, radiation protection, and a growable technology that enlarges the habitat as economics allow" (R. Goyal et al, September 2017, M. Chen et al, August 2020)

System-o-Systems Context and Literature Review-3

- The design and development of human habitation infrastructure in space will be complex but Conditions of human experience comparable to terrestrial environment must be addressed. (M. Chen et al. April 2021, J. B. Hollander, February 2023, R. Rolffs et al, February 2023)
- Despite our current knowledge, experience and understanding of human habitation in space for long-durations, physical human challenges are still abundant.
- "As mission durations gradually lengthen, the next obstacle is a set of physical limitations. Extended exposure to microgravity poses multiple threats to various bodily systems. Two of these systems are of particular concern for the success of future space missions" (A.J. Dontre, February 2024).

System-o-Systems Context and Literature Review-4

- Robots could address some of the physical human concerns in space but may not be sustainable. Utilization of robots and other types of advanced technologies have altered the traditional way of maintaining space projects, which can further help in colonization process and habitat maintenance. (S.K. Basha et al., September 2022).
- Humans are social beings, so conditions for space habitation are expected to mirror social aspects in terrestrial environments. Despite best efforts, achieving optimum social objectives in terrestrial SoS remains a challenge: the American with Disability Act (ADA) was passed in 1990 but it still remains a challenge implementing it fully.
- Conditions of disability will occur in space so there should be provisions to handle such instances of and human conditions. The complexity in space could only be imagined (T. Gres et al, October 2023)

SoS Challenges -1

- Elicit questions to address the key characteristics of SoS in the context of the three system domains that will proliferate in SoS suitable for human habitation in space.
- These questions should lay the baseline for further decomposition to broaden understanding, provoking high-level conceptual ideas. Consequently, the key characteristics of SoS are further explored to elicit pain points.
  - **Independence:** The independence characteristic of SoS emphasizes autonomy, decentralization, interoperability, modularity, redundancy, self-organization, and resource management of the constituent systems within the SoS.
  - **Interconnectivity**: The interconnectivity characteristic of SoS depends on robust communication infrastructure, data exchange standards, real-time information sharing, integration interfaces, dynamic adaptation, security measures and scalability.

SoS Challenges -2

- SoS challenges continue…
  - **Emergent behavior:** The emergent behavior characteristics in SoS arises from the complex interactions and synergies among individual systems, resulting in novel properties and behaviors at the SoS level, which are not predictable from the behavior of individual systems alone.
  - **Complexity:** The complexity characteristic of SoS is a result of some key attributes: heterogeneity, interdependence, scale, dynamic environment, emergent behavior, information flow. Also, organizational factors inherent in the design, operation, and management. Understanding complexity is essential to ensure successful SoS deployment.
  - **Dynamic Nature:** The dynamic nature characteristic of SoS reflects its ability to adapt, evolve, respond to changes in its environment and operational context. This dynamic behavior is driven by factors such as adaptability, flexibility, interactions, feedback loops, emergent behavior, real-time decision-making, and continuous improvement efforts.
  - **Distributed Control:** The distributed control characteristic of SoS emphasizes decentralized decision-making, autonomy of individual systems, local optimization, inter-system communication, resilience, scalability, and adaptability.

SoS Methodologies and Approaches Consideration -1

- Each of the SoS characteristics are associated with attributes, introducing more complexity
- Comprehensive management of SoS management must explore influences and impact of the associated attributes

SoS Characteristics					
Independence	**Interconnectivity**	**Emergent Behavior**	**Complexity**	**Dynamic Nature**	**Distributed Control**
Autonomy	Communication Infrastructure	Complex Interactions	Heterogeneity	Adaptability	Decentralized Decision-making
Decentralization	Data Exchange Standards	Synergy	Interdependence	Flexibility	Autonomous Systems
Interoperability	Real-time Information Sharing	Non-determinism	Scale	Interactions and Dependencies	Local Optimization
Modularity	Interation Interfaces	Adaptability	Dynamic Environment	Feedback Loops	Inter-system Communication
Redundancy	Dynamic Adaptation	Resilience and Robustness	Emergent Behavior	Emergent Behavior	Resilience and Redundancy
Self-organization	Security Measures	System-level Properties	Information Flow	Real-time Decision-making	Scalability
Resource Management	Scalability	Understanding and Management	Organizational Complexity	Continuous Improvement	Adaptability

SoS Methodologies and Approaches Consideration -2

- Proliferation of SoS will be the norm and owned by varying entities with diverse mission objectives
- Develop Multimodality Transfer Functions (MTF) to address complexity of SoS management in a multi-vendor environment
- MTF will provide a disciplined and orchestrated SoS ecosystem management regime
- High-level questions to provoke elicitation of relevant pain points.
  - How will independence be managed to facilitate cooperation of competing companies?
  - How will interconnectivity be managed to facilitate cooperation of competing companies?
  - How will emergent behavior be managed to facilitate cooperation of competing companies?

SoS Methodologies and Approaches Consideration -3

- High-level questions to provoke elicitation of relevant pain points.
  - How will complexity be managed to facilitate interoperability of competing companies SoS ecosystems?
  - How will dynamic nature be managed to facilitate cooperation of competing companies?
  - How will distributed control be managed to facilitate cooperation of competing companies?
  - What is the appropriate framework for the development of MTFs?
  - How can terrestrial SoS best practices be leveraged?
  - What is the appropriate framework for addressing a competitive business environment?

Lessons learned from Terrestrial SoS deployment

- It is difficult to manage terrestrial SoS due to the characteristics discussed. Nevertheless, much as been done to establish some standards that makes the task manageable in terrestrial deployment.
- Air transport System is a terrestrial SoS that displays a managed SoS ecosystem – MTF concept exemplar
  - Accessibility of SoS
  - Reliable communication between stakeholders
  - Travel requirements to SoS infrastructure and installations are routine and affordable
  - In-person technical interchange meetings schedule is easily manageable
  - Etc.

Lessons learned from Low-orbit SoS Deployment

- Much has been learned from the operation of the International Space Station (ISS) system. An ecosystem that exhibit various SoS characteristic challenges
- Governed by a single entity (agreements/treaties)
- Every constituent system adheres to and satisfies high-level requirements
- Centralized communication, operation and control
- Established set of common interfaces
- A well defined SoS management regime - think MTF concept
- Hubble Space Telescope
    - The challenges to repair the defective mirror/lens was a reminder of how difficult it is to manage a system in space

Concluding Remarks

- The paper discussed the case for SoS in space exploration and human habitation.
- An attempt has been made to highlight challenges and considerations envisioned in SoS deployment
- Considerations for methodologies and approaches to mitigate SoS management challenges is discussed.
- A concept for development of Multimodality Transfer Functions (MTF) for constituent systems is proposed.
- Some high-level questions are posed to provoke elicitation of relevant pain points and questions
- Recommend research work on MTF development to gather empirical data that is qualitative, quantitative and actionable

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