MODELING CHALLENGES FOR EARTH OBSERVING SYSTEMS OF SYSTEMS

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ABSTRACT

Earth observing systems are undergoing an architectural transformation to perform novel scientific campaigns by dynamically composing assets from government and commercial partners. Correspondingly, campaign-level engineering methods and tools must accommodate greater degrees of decentralized control and independence. This paper reviews advances provided by semantic web technology and distributed simulation to highlight some of the challenges in modeling Earth observing systems of systems. A campaign simulation framework organizes the contextual, structural, and behavioral features necessary to model Earth observing systems from a system of systems perspective. Finally, a multi-actor value framework considers interactive negotiation of non-commensurate preferences by participating entities.

Index Terms— Earth observation, system of systems, model interoperability, campaign simulation

1. INTRODUCTION

As a part of a broader shift in space systems engineering, the Earth science domain is undergoing an architectural transformation enabled by advances in technology, component miniaturization, and reductions in launch costs. Future observation strategies will supplement traditional government spacecraft with a broader mix of distributed platforms including non-government assets under policy frameworks such as the NOAA Commercial Space Policy [1] and Weather Research and Forecasting Innovation Act of 2017 [2]. Pilot programs with NASA and NOAA are already underway to purchase data from commercial small-satellite constellations [3, 4].

Coordinating decentralized control of government and commercial assets highlights the operational and managerial independence common in systems of systems [5]. Rather than being designed from scratch by a single entity, systems of systems compose existing assets to produce desired emergent behavior and rely on aligning incentives to ensure participation. This indirect level of control presents challenges to systems engineering activities and emphasizes greater levels of interoperability in supporting models and simulation [6].

This paper addresses some of the fundamental modeling challenges facing conceptual design of Earth observing systems of systems. It reviews related work in model interoperability and outlines a potential simulation framework to compose models. Resulting campaign-level models seek to evaluate proposed concepts from a multi-actor perspective to understand and anticipate strategic behaviors on behalf of interacting stakeholders.

2. MODEL INTEROPERABILITY

As a reflection of the intended system architecture, system of systems models often require greater degrees of decentralized control or independence among modules or components. Coordinating models requires a degree of conceptual interoperability which can be oriented on a six-item scale [7]:

1. Technical: common information exchange mechanism.
2. Syntactic: common data syntax or structure.
3. Semantic: common data semantics or vocabulary.
4. Pragmatic: common context of data workflow or usage.
5. Dynamic: two-way interactive information exchange.
6. Conceptual: mutually compatible conceptual model.

From a basic level, establishing technical interoperability can be as simple as exchanging files; however, achieving higher levels of interoperability by aligning data syntax and semantics presents major theoretical and practical challenges due to differences in level of abstraction, core assumptions, and even norms adopted by differing organizations. The ideal state of conceptual interoperability would allow seamless model composition for system of systems engineering. The remainder of this section reviews two approaches to establish model interoperability from static and dynamic perspectives.

2.1. Semantic Web Technology

Semantic web technology embodies a set of related standards primarily published by the World Wide Web Consortium

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Supported by NASA grant number 80NSSC17K0586.

(W3C) to promote machine readability for web applications. While typically oriented for static exchanges (i.e. semantics), it provides an essential basis for interoperability.

The semantic web builds on the Resource Description Framework (RDF) as a foundational concept to express information as a graph of "triples" connecting subjects and objects (nodes) with named properties or predicates (edges) [8]. Standards for eXtensible Markup Language (XML) and JavaScript Object Notation for Linked Data (JSON-LD) provide common syntax for RDF data. Extensions to RDF such as RDF Schema (RDFS) support taxonomic abstractions such as class hierarchies and property domains/ranges [9].

Building on RDFS, the Web Ontology Language (OWL) provides greater expressiveness to differentiate between universals (classes) and individuals (instances) and define logical restrictions on class membership and data or object properties [10]. Sophisticated ontologic rule sets can enable automated reasoning or inferencing based on an open-world assumption where missing information is inferred by logical deduction. Upper-level ontologies such as the Basic Formal Ontology (BFO) provide a consistent worldview to help merge separate ontologies [11]. Some science domains such as marine research publish and maintain ontology repositories [12]. While there have been several efforts to create vocabularies specific to the Earth science and space systems [13, 14, 15], there is no widely-adopted standard used in practice.

Despite the technical capabilities of OWL, it has seen limited use in practical web applications due to a high degree of complexity and difficulty in standardizing expressive vocabularies. Competing approaches such as Schema.org are based on simpler frameworks while still drawing from linked data representations of RDF and RDFS [16]. Combined with user-friendly syntax such as JSON-LD, Schema.org has realized higher levels of adoption by web applications but has not yet been applied to engineering model interoperability.

2.2. Distributed Simulation

Distributed simulation covers a set of standards largely developed within of the defense domain to integrate simulations controlled by different partners (e.g. aligned military branches or nations) or contractors using proprietary information [17]. In these applications, the large scope and organizational barriers prevent direct integration of simulation models and data is exchanged using local or wide area computer networks.

Real-time protocols used for wargaming exercises include Distributed Interactive Simulation (DIS) which provides an interface and a common syntax for line-level information exchange during a distributed simulation [18]. DIS uses a Protocol Data Unit (PDU) to define platform-specific vocabularies for simulation state information. Given its real-time nature, DIS is most frequently used in training or verification, validation, and testing activities.

The High Level Architecture (HLA) is a related standard supporting general-purpose simulation including non-real-time [19]. It defines a common software application program interface (API) to a runtime infrastructure (RTI) which exchanges data during a federated simulation. RTI synchronization algorithms enforce temporal causality and avoid live- or dead-lock conditions during time managed simulations. The HLA allows custom vocabularies composing primitive types documented in a federation object model (FOM) and follows expected dynamics described in a federation agreement. To promote compatibility with legacy DIS applications, PDUs have been published as a standard Realtime Platform Reference (RPR) FOM [20].

The HLA and a domain-specific Space Reference FOM have recently applied to the space systems domain in the context of human exploration to coordinate mission simulation between agencies [21]. Some of the key elements of the Space Reference FOM include modeling spacecraft state variables, reference frames for coordinate system transformations, and various time scales.

3. CAMPAIGN SIMULATION FRAMEWORK

Earth observing systems of systems should viewed as an integrated campaign of individual assets and missions operated by participating entities. A campaign-level simulation must be able to compose a set of interdependent mission models which interact with each other through a well-defined interoperability interface. Irrespective of the underlying interoperability approach, campaign-level simulation relies a consistent framework to integrate member models.

This section describes how the Infrastructure System of Systems (ISoS) framework, originally developed to model strategic interdependencies between infrastructure systems, could be adapted to increase conceptual interoperability between constituent models [22]. Informed by past applications to federated satellite systems [23], this section organizes model state and state transitions using a logical description of the model context, structure, and behavior.

3.1. Contextual Model

The contextual model establishes consistent representations of space, time, and data primitives such as resource types fundamental for exchanges across system boundaries.

Although the original ISoS framework prescribes a discrete spatial model, Earth observing systems rely heavily on a geometric interpretation of spatial trajectories and phenomena. At least two reference frames are required to express most concepts. First, surface, sea, or aerial platforms use an Earth-fixed frame with transformations between Cartesian and geodetic coordinates such as the World Geodetic System (WGS) 84 model. Second, space platforms use an Earth inertial frame (independent of Earth's rotation) with transformations between Cartesian and Keplerian orbital elements.

Depending on the implementing technique, a campaign-level simulation may tolerate slightly different temporal resolutions; however, the composite model must adopt a consistent time scale to represent global operations. Common time scales used in the space systems domain include Coordinated Universal Time (UTC) and Terrestrial Time (TT) but others such as Julian Day or Modified Julian Day are also used. Detailed operational models may need to account for complexities such as leap periods when translating between time scales and Gregorian calendar representations such as ISO-8601.

Finally, other data primitives may be needed to express quanta exchanged across system boundaries. The primary resources managed in Earth observing systems include information and currency; however, future concepts of operation may include a larger set of services such as propellants/fuels and energy exchanged between assets.

3.2. Structural Model

The structural framework expresses model state as the set of information to recreate a snapshot in time. It is expressed in terms of schemas or ontologies for semantic web applications and PDUs or FOMs for distributed simulation. From the perspective of an interoperability interface, only the model state relevant for interactions across system boundaries must be exposed with particular emphasis on communications systems.

An Earth observing system is composed of multiple space- and non-space platforms called elements. The most essential state variables for each element includes its spatial location including position, velocity, and attitude quantities within a contextual reference frame. Velocity is particularly important for dead reckoning interpolation and Doppler shift calculations. Other relevant information required at higher levels of model fidelity include technical descriptions of communication systems such as transmission frequencies, antenna diameter, gain, power, and losses.

3.3. Behavioral Model

The behavioral framework expresses valid state transitions executed in response to system functionality resulting in an updated state value or message. In distributed simulation, behaviors are communicated with PDU exchanges or FOM object or interaction updates.

While highly specific to each use case, there are generally five types of system functions: transforming from input to output resources (e.g. using an instrument to record an observation), transporting from an origin to a destination (e.g. transmitting data on a communications link), storing or retrieving resources (e.g. writing data to memory), exchanging resources across system boundaries (e.g. selling data or data services), and controlling an element by prescribing functions to execute (e.g. instructions for any of the above). Of these behaviors, only the exchanging resources function must be exposed to the interoperability interface.

4. MULTI-ACTOR VALUE FRAMEWORK

Simply performing a technical simulation analysis is not sufficient to address challenges in Earth observing system of systems. The presence of multiple actors introduces new sources of complexity related to the interpretation and pursuit of individual potentially-competing objectives. Models should also be used as a social platform to communicate objectives and preferences among interacting stakeholders. At the system of systems level, participation is not guaranteed and composing systems must be treated more like a negotiation.

Collaboration in engineering design poses several practical and theoretical challenges. For example, consider the engineering collaboration via negotiation (ECN) model of engineering decision-making [24]. Interactions among stakeholders must be carefully managed to ensure adequate representation and appropriate communication channels. Interactive modeling sessions help stakeholders to construct a common understanding of the problem and, once attained, productively discourse group preferences. Finally, collective agreement can be achieved by negotiating on shared and competing objectives with respect to the group preference.

Multi-actor value modeling views Earth observing campaigns more like a game than an optimization. There is no single objective function and individual stakeholders may have difficulty expressing their own preferences, let alone others'. There is a significant amount of research to consider economic incentives or mechanisms to encourage participation in distributed systems at the forefront of systems engineering.

5. CONCLUSION

Advancing new Earth observation strategies by composing distributed assets operated by multiple partners faces significant modeling challenges. Constituent models must conform to an interoperability interface to control information exchanges across organizational boundaries. A campaign-level simulation framework can help to normalize model state and state transitions at an abstract level. Finally, corresponding analysis must be treated as a multi-actor value problem rather than an optimization to reflect the lesser degree of control over design concept selection and operation.

This paper highlights some of the existing work from other domains including information technology (e.g. semantic web technology) and defense or combat simulation (e.g. distributed simulation standards) the Earth science community can leverage for modeling systems of systems.

6. ACKNOWLEDGMENT

This work was funded by NASA's Goddard Space Flight Center under grant number 80NSSC17K0586 in support of an Earth Science Technology Office (ESTO) Advanced Information Systems Technology (AIST) 2016 project.

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