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ON THE ROLE OF HLA-BASED SIMULATION IN NEW SPACE

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ABSTRACT

This paper discusses High Level Architecture (HLA) based simulation in the context of the emergence of the private spaceflight industry called New Space. We postulate that distributed simulation plays a fundamental role in facilitating new opportunities of a cost efficient access to space. HLA defines a simulation system's architecture framework with a focus on reusability and interoperability. The article will therefore discuss the impact of its usage on the potential of affordable new aerospace systems developments. Future possibilities with an increased level of loose component coupling are presented.

1 INTRODUCTION

Although the Space Frontier Foundation defines New Space as "People, businesses and organizations working to open the space frontier to human settlement through economic development" (Denis et al. 2020), there is no unified definition of the term New Space, because its main today's usage is ruled by a clear buzzword character. A common understanding can be derived by looking at the main difference to "Old Space". Traditionally, space activities were mainly ruled by a dependency on government agencies. An increasing transition to private companies could be identified in the younger past. Against the background that the beginning of this change dates back to the late 1990's, the term "new" in New Space gets its relativization. The trend to mega constellations of small satellites in conjunction with the economic potential of spaced-based services are the main drivers for commercialization today. Companies which take lessons learned from the early New Space days are in a position to realize substantial financial returns. One of the main reasons for that is the establishment of standardized form factors and interfaces. Standardization with its advantages of predictability and consistency is the key factor.

As distributed simulation is an important tool in the area of space systems testing and mission preparation, re-usability of components and "do not re-invent the wheel" are substantial aspects for keeping efforts in a harmonized balance to the overall budget. This is where HLA as a de jure as well as de facto standard (Topçu and Oğuztüzün 2017) fits perfectly in. It defines a common architecture for distributed simulation. Simulations running on separated computers can be combined to one federation. The data to be exchanged is defined in a Federation Object Model (FOM) which specifies associated interactions and objects. Reuse of components is simplified by decreasing their communicational interdependency. This is achieved by a central communication component called Run-Time Infrastructure (RTI) which provides software services for the data exchange and operations coordination between the simulation federates. In order to establish a-priori interoperability for complex systems, domain specific reference FOMs (e.g. Real-time Platform Reference Federation Object Model (RPR FOM), Medical FOM, Air Traffic Management (ATM) FOM ED147 B) exist. The Space Reference Federation Object Model (SpaceFOM) is the latest release in this area. It provides a standardized way for the combination of simulations in the space domain with a focus on system reusability. Obeying to the SpaceFOM ensures independent developments of different simulations on the one hand and the certainty that these systems will interoperate on the other hand, thus settling an interoperability before integration tests (Crues et al. 2021).

In this article we argue that the usage of HLA in combination with the SpaceFOM is a key enabler for cost effective complex space related simulations in the New Space community. Minimizing the harmonization and integration effort for repeated operation in new distributed constellations is of utmost importance for the sustainability of system specific targeted simulations. A higher degree of loose coupling with the future HLA 4 standard will open new possibilities for operation system and implementation language independent approaches.

The other sections of this paper are structured as follows. Section 2 gives an overview about current and future aspects of New Space. Section 3 discusses the role of simulation in New Space. A derivation to associated aspects for HLA is presented in section 4. Section 5 closes with a summary.

2 NEW SPACE

2.1 Characterization

New Space is characterized by a clear focus on customized development of services and products with a strict cost-reflectiveness. Peeters (2021) distinguishes three space business phases and refers to the third phase, since the year 2000, as New Space. The convergence with the IT sector can be regarded as a main driver and is twofold: On the one hand there is an increasing demand for global services and products from the IT sector with respect to a world-wide broadband coverage for the Internet of Things (IoT), Big Data and location based services, on the other hand business models and services like cloud computing are transferred from the IT sector to New Space (Horn et al. 2016).

2.2 Areas and Timeline

Figure 1 gives a non-exhaustive overview of New Space topics in a floating timeline from present to future. It must be emphasized that the timeframes have to be regarded as very rough estimations. With the increasing demand for data services based on small satellites, air launch is one of the leading alternative concepts to meet the requirements for low cost access to orbit (Sarigul-Klijn et al. 2005). A rocket with the target payload is attached to a carrier aircraft. It performs a horizontal-takeoff and takes the rocket to the launch region where it is ejected at an altitude comparable to the aircraft's normal cruise altitude. Piggyback payload refers to the utilization of remaining payload capacity of a big satellite launch for additional smaller satellites. The topic of space debris avoidance mainly covers two areas: avoiding the creation of debris and avoiding collisions with existing debris objects. The first refers to passivation of objects in orbit at their lifetime's end, the latter is achieved by collision avoidance maneuvers of active objects. Space debris removal and space tourism are business fields of the future. Although some passenger spaceflights have already taken place, the term "tourism" would be misleading with respect to these recent activities. The ClearSpace-1 mission (Clearspace today 2022), with a planned launch in 2025, will be the first space debris removal mission. Farer future commercial relevance refers to suborbital travel, production in space, space mining and habitats in space. Virgin Galactic conducted a successful passenger suborbital flight in July 2021. Such flights with more passengers, on a regular basis and on longer point-to-point distances still need fundamental concept considerations for their integration in normal air traffic in non-segregated airspace. The Chinese space plane company Beijing Lingkong Tianxing Technology Co., Ltd. plans first suborbital point-to-point crewed travel test flights by 2030 (Jones 2022), which can be regarded as extreme ambitious in this context. Production in space is mainly represented by two areas. The first aspect refers to the assembly of space systems in space, thus breaking free from launcher's design, its space limitations and the need to overcome the gravitational forces when building the complete system on Earth. The second aspect covers new product properties enabled by the production in absence of gravity-driven phenomena. Space mining relates to the mining on celestial bodies. Where the Moon, thanks to its relative close distance to Earth, is likely to become the first commercial space mining target, asteroids with their long distances to Earth and the associated energy needs and travel times have to be contextualized as very far future candidates. The term space habitat is dedicated to a self-sustaining environment for permanent settlement in an orbit or outer space. Up until now, none has been built. Taking into account that there is still a lack in elemental solutions for long lasting heat, meteoroid and radiation protection, food production or synthetic food substitution, atmospheric control and artificial gravity, space habitats can also be characterized as a farer future New Space area.

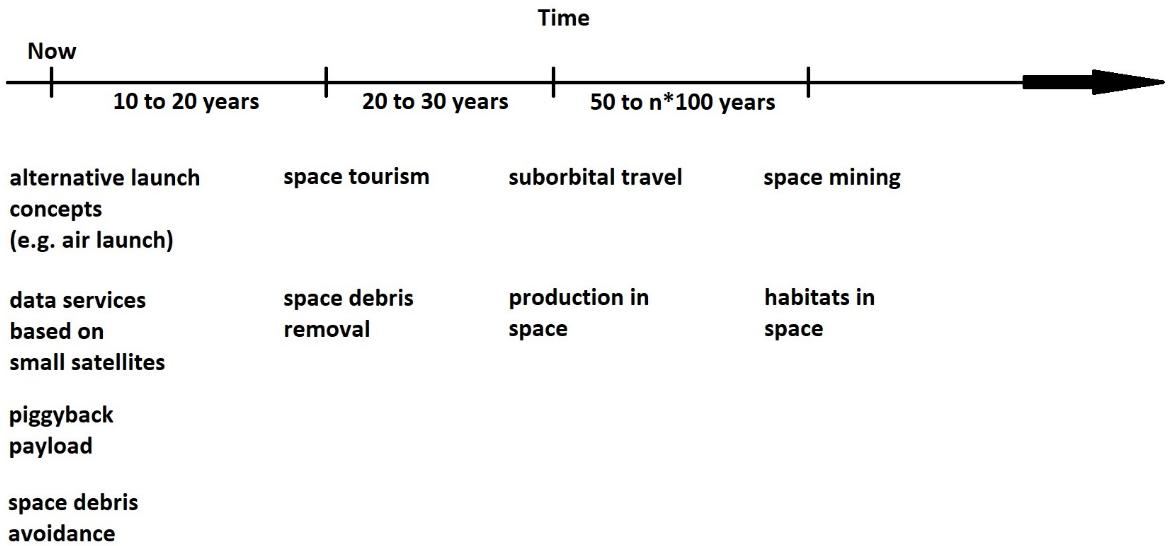

Figure 1: New Space topics in the timeline from present to future (schematic view, time axis not to scale).

3 SIMULATION IN NEW SPACE

3.1 Need for Simulation

Space related systems or operations are mostly characterized by a high degree of complexity in combination with harsh environment conditions. Therefore simulations are a key enabler in the preparation for effective and safe handling and to reduce the potential of upcoming dangerous situations. This can address specific questions as well as generic aspects. As an example, pilots of a space vehicle must be trained for the needed general handling routines on the one hand and being prepared to perform the right actions at the right time in emergency situations under off-nominal conditions on the other hand. Regarding the development of satellites, high levels of reliability and autonomy must be achieved to offer associated data services at a reasonable price. Testing under realistic conditions is hard to achieve. This is why development and verification must be supported by appropriate simulations (Hendricks and Eickhoff 2005).

3.2 Need for Distributed Simulation

The strict market orientation of New Space opens new possibilities and a new growth in the space industry sector (Horn et al. 2016). Taking related chances requires a flexible sensitivity for market opportunities with a high degree of cost effectiveness and the ability to cooperate with partners distributed around the world. Its implication on simulations leads to the fundamental need for realizing complex systems with a clear focus on network-centric modelling and simulation (M&S) application-level reusability of chosen models. Reusability defines the capability of an artifact of being used again (Balci et al. 2011). Composability is a second M&S characteristic for reducing modelling effort and is defined as the capability of being constituted by combining things, parts or elements (Balci et al. 2011). Thus a high degree of composability allows component assembly variations to address the satisfaction of a variety of requirements. HLA in principle allows composability of simulation components in a plug-and-play manner (Strassburger 2006b). Distributed simulation based on the HLA can therefore be regarded as a core enabler for facing the New Space challenge of fast reaction to market opportunities while "designing" safety from the beginning in terms of:

- analyze systems in advance,
- validate concepts and operations before these are put in place,
- check procedures before they are used in training,
- train procedures and handling.

Especially simulation based training provides new possibilities for human-in-the-loop full mission testing and training for the sake of mission success and safety in combination with reduced time and costs (NASA Technology Taxonomy 2020). As an example, the ability to manually maneuver a spacecraft (e.g. docking to a space station) is still an important asset in human spaceflight, although most standard procedures are ruled by fully automated processes. Astronauts must be able to manually steer in case something goes wrong. Six degrees of freedom control while always having a clear situation awareness about the own position and orientation in space is the related crucial task. The associated skill must be acquired and continuously checked by dedicated human-in-the-loop simulations. Another aspect refers to the establishment of test environments for the introduction of new technologies. As an example, simulation tests with 3D presentation versus 2D human machine interface (HMI) for spacecraft docking procedure training revealed that the identified small benefit is not in balance to the larger costs and operational limits of 3D systems (Piechowski et al. 2020). Simulation based training is also important for the preparation of satellite launch campaigns. Here, teams from different areas like ground systems, flight control and satellite provider are gathered in a mission control team. Then, this joined team is trained with a focus on the dedicated mission with respect to the standard procedure handling of its launch and orbit phase. Additional training sessions cover the aspect of fast and effective reactions to off-nominal events. This whole simulation phase does not only address the joined teams, it also needs the integration and interplay of the related different systems. In summarized words, a team of teams has to be trained to handle a system of systems. This emphasizes the character of combining distributed assets to one whole setup where distributed simulation is the right choice for realization.

3.3 Need for Loose Coupling

With more and more New Space players competition will increase, thus being fast and flexible in a cost-effective way will become more and more important. The translation to distributed simulation of complex systems results in the need for software extensibility and scalability. This is where tightly coupled solutions have clear losses. Their purpose-built character needs more integrations and resources when simulation scenarios evolve and need changed and/or additional components because of finer grained conditions and requirements. Loose coupling potentially enables the transformation of existing solutions, originally not planned for a complex interplay environment, to valuable federates with less effort. This gets even more significant if programming language independency is concerned. Figure 2 shows the principle of component interchangeability. Different federates (1 to n) responsible for different jobs can be represented in different realization versions (_1 to _n) providing different realization types. An example is given in Table 1. Federate 1 provides a flight dynamics model where the different realization versions, developed in various programming languages, cover evolving quality levels ranging from a simplified point-mass model to sophisticated aeroelastic flight dynamics. The same principle refers to Federate 2 where thrust is simulated in a simplified manner without transient regimes, with an advanced model taking into account transient regimes and according to a more advanced model reflecting even modulations by fuel injection rate variations. To improve the quality of a whole complex federation, different realization versions (_1 to _n) of the federates often need combination in a mixed way (e.g. 1_3 together with 2_1). Establishing these combinations with a minimum of programming effort is of fundamental character for cost efficient approaches, thus loose coupling possibilities are of elemental importance.

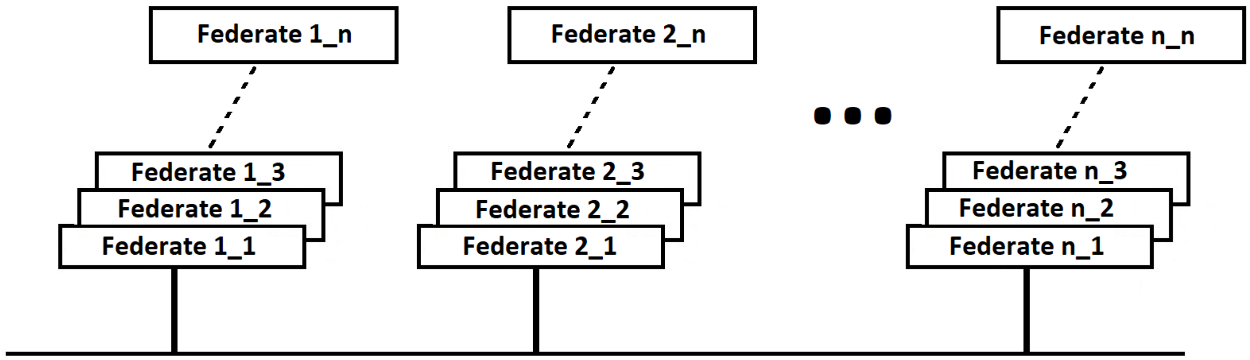

Figure 2: Component interchangeability.

Table 1: Component interchangeability example.

Component	**Type**	**Realization Version**	**Realization Type**	**Programming Language**
Federate 1	Flight dynamics model	Federate 1_1	Point-mass model (simplified)	Java
		Federate 1_2	Aerodynamic model	C#
		Federate 1_3	Aeroelastic flight dynamics	C++
		…	…	…
		..	..	..
		.	.	.
Federate 2	Thrust model	Federate 2_1	Model without transient regimes (simplified)	Javascript
		Federate 2_2	Model with transient regimes	Python
		Federate 2_3	Model with transient regimes and modulations by injection rate variations	Fortran
		…	…	…
		..	..	..
		.	.	.

4 HLA IN NEW SPACE

4.1 History of HLA

A brief version history of HLA is shown in Figure 3. A more detailed discussion of HLA's early history can be found in (Strassburger 2006a). In short, the combined experiences from Distributed Interactive Simulation (DIS) and the Aggregate Level Simulation Protocol (ALSP) led to the first published HLA version named HLA 1.3 in 1998. With improvements related to data distribution management and the federate object model (FOM), it was published in late 2000 by the Institute of Electrical and Electronics Engineers (IEEE) as HLA 1516-2000 and was approved by the American National Standards Institute (ANSI) in early 2001. Further improvements dealing with dynamic link compatible (DLC) application programming interfaces (API), a Web Services API and modular FOMs resulted in HLA 1516-2010 (also called HLA Evolved) in 2010. A new version, expected to be named HLA 4, is under development at the Simulation Interoperability Standards Organization (SISO) since 2016 and still ongoing.

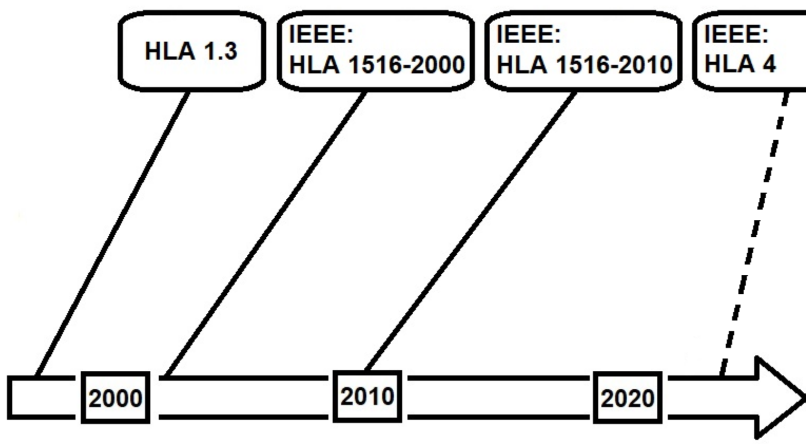

Figure 3: History of HLA.

4.2 Interoperability

Evaluations of the benefits of distributed simulations carried out by the European Space Agency (ESA) resulted in the first ever applications of the HLA standard to the space domain (Arguello and Miro 2000). The National Aeronautics and Space Administration (NASA) conducted a comparable study in the same year (Reid and Powers 2000). Subsequently, HLA was used in the space community for a series of simulations. Some (among others) of the related federations referred to (Crues and Möller 2020):

- ESA / Russian Mission Control Center simulations for the Automated Transfer Vehicle (ATV) docking to the Russian segment of the International Space Station (ISS),
- ESA / NASA rendezvous and docking simulations,
- ESA / Japan Aerospace Exploration Agency (JAXA) rendezvous simulations.

In the context of a NASA led project for a simulated lunar mission called Simulation Exploration Experience (SEE), a framework called HLA Development Kit Framework (DKF) proved its effectiveness by an additional abstraction layer, which hides the HLA specific and complex functionalities, thus facilitating federate development (Falcone et al. 2017).

Although HLA as an open standard proved its efficiency for system reuse and combining in the space domain, HLA alone cannot guarantee interoperability, especially if the establishment of its a-priori type is concerned. The concept of a-priori interoperability refers to the provision of a codified process for federate creation that makes a federation work without the need for supplemental integration and negotiation (Crues et al. 2021). To cover this aspect, domain specific standardization on FOM level is needed. This was already established in terms of some so-called reference FOMs, but their support for space domain specifics was not adequate. Many large-scale HLA simulations are based on the RPR FOM (Simulation Interoperability Standard Organization 2015), which is limited in its suitability to model systems much beyond the Earth's atmosphere (Simulation Interoperability Standard Organization 2019). The main reasons for this limitation are the RPR FOM's property of using a geocentric coordinate system and a non-standard time-stamping approach (Möller et al. 2016a). To overcome these constraints, SISO started an initiative to develop a Space Reference FOM (Möller et al. 2016b), which resulted in its version 1.0 standard in 2019. The main features for the establishment of an a-priori interoperability are:

- a space systems domain specific hierarchy definition of interaction classes and objects,
- time management specific definitions,
- a flexible positioning system with reference frames.

First experiences revealed that the SpaceFOM successfully supported the development of a baseline federation and its re-usage to represent a starting ensemble for future adaptation needs (Möller et al. 2021).

4.3 Loose Coupling

Since version IEEE 1516-2010, the HLA standard provides a Web Services API with the possibility to build federations based on loosely coupled web client federates, thus generally establishing a way to combine HLA with Modelling and Simulation (M&S) as a Service (MSaaS). The Web Services API provides the HLA services as Extensible Markup Language (XML) payload in requests and responses over http/https. This synchronous request/response pattern with the use of blocking calls and CPU resources hungry XML processing, although good enough for a certain range of applications, has a significantly lower performance than traditional federations where each federate uses Local RTI Component (LRC) library calls. The next version of HLA called HLA 4 aims at keeping the loose coupling advantage of the Web Services API and overcome most of its drawbacks. Providing HLA services over a standardized binary federate protocol will be the solution there (Möller et al. 2018). A Tiger Team from the HLA 4 product development paved the way in the direction of a standardized protocol specification which keeps the advantages of the WSDL API on the one hand and removes most of the limitations on the other hand (Möller et al. 2022). For the realization of the services layer, Protobuf (Google Developers 2022) was selected with a mapping of the HLA service calls to Protobuf messages (Möller et al. 2022). In Protobuf, a schema for binary encoding of the data under consideration can be defined in an dedicated specification language. For the once defined data structure read and write operations related source code will then be generated for a variety of target languages with the help of a so-called proto compiler. The actual range of supported languages covers Java, Python, Objective-C, C++, Kotlin, Dart, Go, Ruby, and C# (Google Developers 2022). One specification enables the data transfer realization regardless of the implementation language. As a fundamental advantage, the evolvement of the specified schema automatically results in the evolvement of the associated regenerated target language classes, getting rid of the need of hand-coded adaptations. Data fields can simply be switched between "required" and "optional" just by the definition of a new numbered field for the value under consideration. This gives a powerful flexibility encoded into the serialization format semantics. For the communication of the encoded HLA services with matching the related requests and responses and allowing independent federate or RTI side initiation of calls and callbacks, a new session layer protocol was developed (Möller et al. 2022). The benefits of combining the future HLA 4 standard with the SpaceFOM are shown in Table 2. Sole usage of the IEEE 1516-2010 Web Services API results in loose coupling, but limited to synchronous communication and without a-priori interoperability. This can be added by the combination with the SpaceFOM. By using HLA 4 with the SpaceFOM, a-priori interoperability will be able to be achieved together with the benefits of loose coupling and asynchronous communication.

Table 2: HLA / SpaceFOM combinations.

HLA Type	**A-priori Interoperability**	**Loose Coupling**	**Loose Coupling with Asynchronous Communication**
HLA 1516-2010 (HLA Evolved)	-	x	-
HLA 1516-2010 (HLA Evolved) with SpaceFOM	x	x	-
HLA 4 with SpaceFOM	x	x	x

4.4 Future Possibilities

This will open new possibilities for the integration of loose coupled federates developed in script languages and scientific and technical computation environments like Matlab, Scilab and Octave. Large and complex federations with a maximum of loose coupling and a minimum of adaptation effort for existing simulations to act as federates will be possible (Figure 4). The elemental New Space principle of saving costs through the combination of existing assets in new ways will find its simulation counterpart. An example of actual work relates to a prototype implementation of the SpaceLiner system of systems concept (Morlang 2021). Here, a human-in-the-loop space flight simulation of DLR’s advanced concept for a suborbital, hypersonic, winged passenger transport vehicle called SpaceLiner is developed as an HLA 4 federation based on the SpaceFOM (Figure 5). Its final target federation mix will combine a maximum of loosely coupled federates with a minimum of tightly coupled ones (Figure 4).

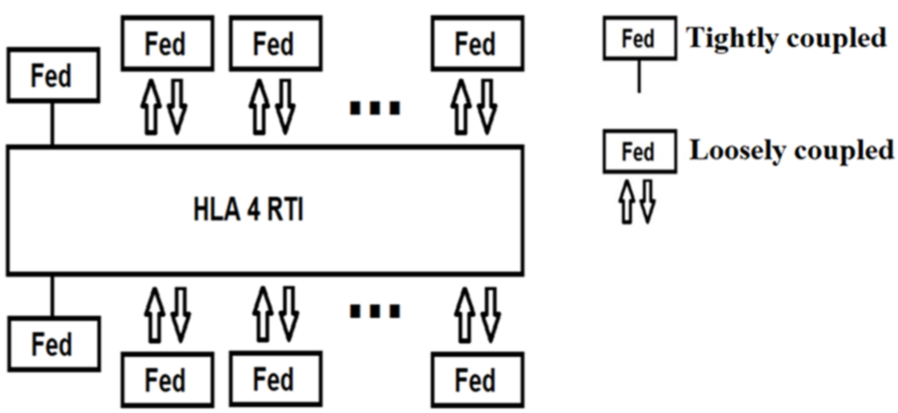

Figure 4: Federation mix with a maximum of loose coupling.

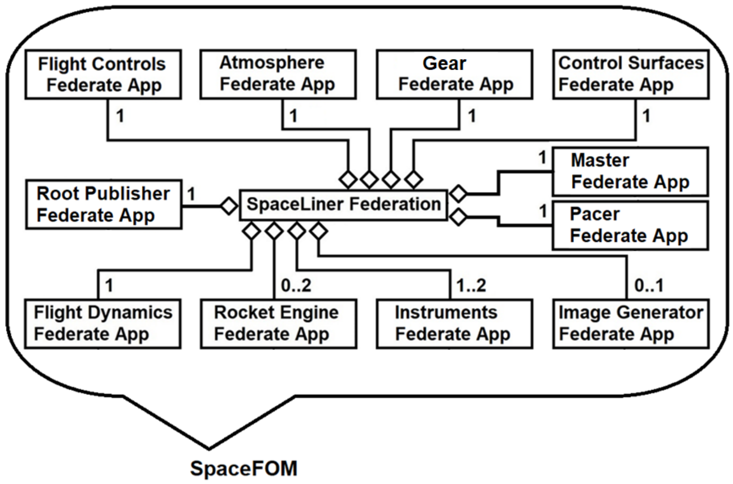

Figure 5: SpaceLiner system of systems concept (Morlang 2021)

Current activities of this work cover the development of two experimental bindings for the Tool Command Language (Tcl) following the HLA 4 Protobuf approach. The first one is based on the incorporation of proto compiler generated C++ classes via the C Runtime In Tcl (Kupries 2022), the second binding uses tclJBlend (Buratti 2022) in combination with proto compiler generated Java classes.

5 SUMMARY

This paper has identified the future HLA 4 in combination with the SpaceFOM as an important success factor for realizing complex distributed simulations in New Space in a cost effective manner. Usage of the SpaceFOM facilitates a-priori interoperability and reuse, which are key factors to construct federations with contributions from different, distributed organizations and keep efforts in a harmonized balance to the overall budget. The paper has reviewed the evolvement of New Space and the need for associated simulations in the space domain. New possibilities of platform and programming language independent loose coupling have been shown, which will take advantage of the new standardized binary federate protocol of HLA 4 and will establish Modelling and Simulation as a Service based on HLA on a new performance level.

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