EXPERIENCES IN USING THE SISO SPACE REFERENCE FOM STANDARD

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ABSTRACT

Due to the increasing complexity of systems in the space domain the management of requirements, emergent behaviors and risks of integrations is becoming a challenging task. Modeling and Simulation (M&S) methods can be usefully exploited to address this complexity and perform a more detailed analysis on the system. In this domain, the IEEE 1516.2010-HLA is one of the well-established standards for Distributed Simulation. Unfortunately, for the different organizations, it is not trivial to implement HLA simulators able to interact with each other. To deal with this aspect and enabling a-priori interoperability between HLA simulators, a Product Development Group (PDG) has been activated to provide a Space Reference FOM (SRFOM) for international collaboration on space systems simulations. This paper presents the most interesting and relevant experiences from the exploitation of the SRFOM standard by the NASA Exploration Systems Simulations team, Pitch Technologies, and the SMASH-Lab of the University of Calabria.

Keywords: Space, Interoperability, High Level Architecture, Federation Object Model.

1 INTRODUCTION

The space domain is characterized by the high cost of real equipment, dangerous scenarios, scarce training opportunities, and emergency operations. As a consequence, Modeling and Simulation (M&S) has always played a key role for supporting space mission analysis, design and operation. Due to the growing complexity of modern space missions, which are often the result of cooperation of many public and private organizations of different countries; Distributed Simulation (DS) represents a fundamental asset that offers functionalities for combining heterogeneous simulation models (made by the same or different organizations), running simulators from different locations, also geographically distributed, and promoting scalability and modularization (Arguello 2001; Bocciarelli et al. 2016; Rabelo et al. 2013).

In the space domain, one of the well-established standards for defining distributed simulation systems is the IEEE 1516 - High Level Architecture (HLA) (IEEE Std. 1516-2010). However, for the different organization involved in simulating a space mission, it is not trivial to implement HLA simulators (called *Federates*) able to interact with each other in a common HLA distributed simulation (called *Federation*). The lack of a common FOM (Federation Object Model) for the space domain is one of the main reasons that precludes interoperability among federates (Möller, Crues et al. 2016; IEEE Std. 1516-2010). Indeed, although a viable solution could be represented by the *SISO RPR FOM (Real-time Platform-level Reference FOM)*, which provides HLA classes and interactions for defining real-time and platform-level federates (SISO-STD-001.1-1999), it is not able to support modeling of systems beyond the Earth's atmosphere. To fill this gap and enabling a-priori interoperability between heterogeneous HLA simulators in the space domain, a Product Development Group (PDG) has been activated in 2015 in SISO with the aim to provide a reference standard, named *Space Reference FOM (SRFOM)*, for international collaboration on space systems simulations (SISO Space Reference FOM (SRFOM) 2019).

The SRFOM standard is composed of two parts: (i) the *SISO Standard for the Space Reference FOM Federation Agreement*, which is a natural language, human readable overview, description and specification of the *SRFOM*; (ii) the *Space Reference FOM*, which is a set of computer-interpretable HLA IEEE 1516- 2010 FOM modules (XML files), designed to be used by HLA runtime infrastructure and other software tools.

In this context, this paper, after an overview of the SRFOM initiative (Section 2), presents the ongoing testing and experimentation activities performed by the NASA Exploration Systems Simulations (NExSyS) team at NASA's Johnson Space Center (JSC), the Labs at Pitch Technologies, and the Systems Modeling and Simulation Hub-Lab (SMASH-Lab) of the University of Calabria (Section 3). Conclusions are drawn and future work delineated in Section 4. Note that the content of this paper is based on the current SRFOM standard draft (SISO Space Reference FOM (SRFOM) 2019).

2 AN OVERVIEW OF THE SISO SPACE REFERENCE FOM

The *SRFOM* standard provides functionalities for enabling the interoperability among HLA-based simulations (*Federations*) in the space domain (Möller, Garro et al. 2016). This includes *Federations* executing in real-time as well as *Federations* executing in logical-time (including as-fast-as-possible). The main objective of the SRFOM is to support training, analysis, mission development and engineering; although other types of usage, like test and concept exploration may also be supported.

Figure 1 depicts the SISO Six-Step standardization process along with its work-products. Concerning the SRFOM, the process started in February 2015 with the presentation of the Product Nomination (PN) approved by SISO SAC (Standards Activity Committee) in April 2015. The activity of the SRFOM PDG started in September 2015 and, after three years of development, the first draft version of the SRFOM standard has been approved for balloting by the SISO SAC in November 2018 and is currently under evaluation by the member of the ballot group.

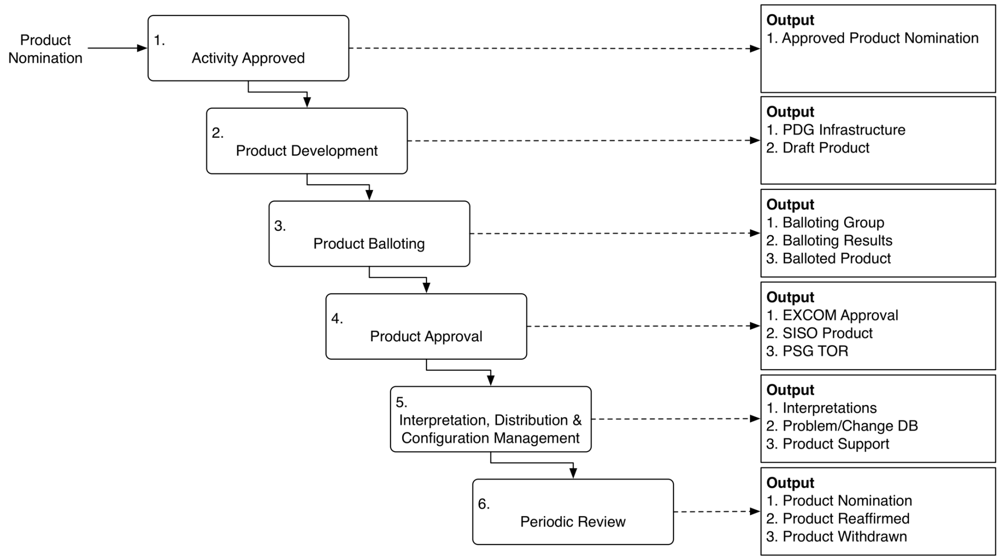

Fig. 1: The SISO Standardization Process.

The SRFOM defined functionalities for managing time and space. Specifically, it defines: (i) a flexible positioning system for bodies in space through Coordinate Reference Frames; (ii) a naming conventions for well-established Reference Frames; (iii) descriptions of common time scales; (iv) federation agreements for common types of time management with focus on time stepped simulation; and (v) support for physical entities (e.g. space vehicles, rovers and astronauts). A description of these first outcomes can be found in (Möller, Crues et al. 2016) and (Möller, Garro et al. 2016). It is worth noting that the SRFOM standard does not define a methodology; therefore, it can be used through the standard HLA DSEEP or FEDEP methodologies (Garro et al. 2018).

2.1 Architecture

The SRFOM defines a hierarchy of *HLAObject* and *HLAInteraction* classes that are managed according to their purposes in separate FOM modules (IEEE Std. 1516-2010). This separation allows developers with a flexible and effective means for handling and extending the standard (see (Möller, Crues et al. 2016; Möller, Garro et al. 2016)). Figure 2 shows the architecture of the SISO Space Reference FOM along with its modules.

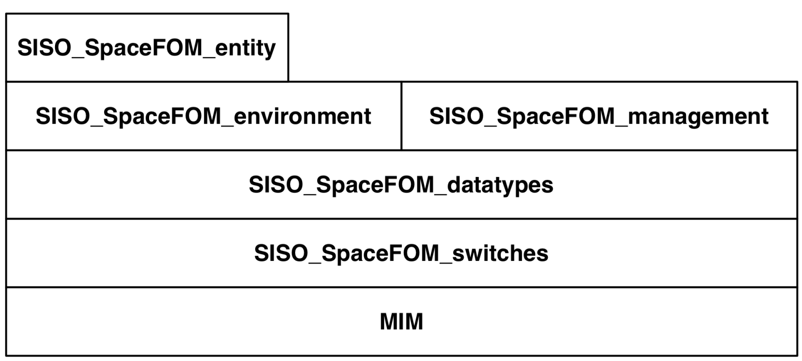

Fig. 2: Architecture of the SISO Space Reference FOM.

The *SISO_SpaceFOM_switches_module* defines configuration settings for managing the Federation execution by way of global Federation execution wide switches for Local Run-Time Component (LRC) and RTI behavior. The HLA standard provides a set of switches that shall be set in the FOM (IEEE Std. 1516-2010). These switches control the behavior of some of the optional actions that the RTI can perform on behalf of the federate, such as automatically requesting updates of an instance attribute when an object instance is discovered or advising the federates when certain events occur. To facilitate easy replacement of these settings, the switches have been confined to the *SISO_SpaceFOM_switches_FOM* module, which federations might choose to update this module based on their federation agreement.

The *SISO_SpaceFOM_datatypes* module offers the definitions of: (i) *HLA simpleDataTypes*, which support management of scalar physical quantities, such as Angle, Mass, MassRate, Velocity and Acceleration; (ii) *HLA arrayDataTypes*, for handling physical quantities managed as vector such as position, velocity and acceleration; and, (iii) *HLA fixedrecordDataTypes*, for managing the space-time coordinates and reference frames' states. Additionally, the *SISO_SpaceFOM_datatypes* defines functionalities for managing the HLA logical timestamp along with the lookahead time (both are represented as 64 bits integers: *HLAinteger64Time*). These data types are used for object attributes as well as interaction parameters and adopt the International System of Units (SI) wherever possible.

The *SISO_SpaceFOM_environment_module* specifies the fundamental data types used to represent the basic physical environmental properties associated with space-based simulations. It specifies the *ReferenceFrame HLAObjectClass* for representing when and where any physical entity exists in time and space.

The *SISO_Space_FOM_management* module offers the specifications for execution control and management of *HLAObjectClass*, *HLAInteractionClass* and *SynchronizationPoint* instances. Particularly, it provides a set of information that are necessary to orchestrate both federation and federate execution time lines and execution mode transitions in a SRFOM compliant federation execution.

The *SISO_SpaceFOM_entity* module delineates the meanings of a space vehicle through the definition of the *PhysicalEntity HLAObjectClass*, which represents a man-made vehicle or a major sub-element of a man-made vehicle. The current definition of the *PhysicalEntity HLAObjectClass* is based on the prototype that has been used in the Simulation Exploration Experience (SEE) project (Falcone and Garro 2016), (Simulation Exploration Experience (SEE) 2019) and that has been improved and extended during the standardization activity.

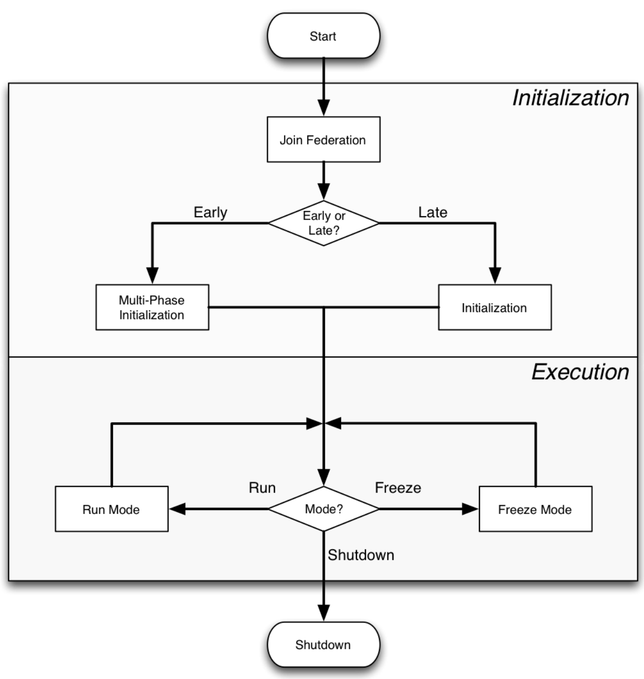

Fig. 3. Simplified Space Reference FOM Executive Flow (SISO Space Reference FOM (SRFOM) 2019).

The interoperability among federates in a federation execution requires not only the specification of the data exchange between federates but also the specification of executive behavior. With this in mind, the SRFOM provides a set of specifications for managing the execution control of SRFOM compliant federates. As shown in Figure 3, the SRFOM executive flow has four principal states: *start*, *initialization*, *execution*, and *shutdown*. The Space Reference FOM designates the role of the Master federate as the principal federate for controlling and coordinating the federation execution. The Master federate makes use of three principal HLA mechanisms to manage execution control: (i) *Execution Control Objects;* (ii) *Mode Transition Request Interactions;* and (iii) *Coordination Synchronization Points* (see (Möller, Crues et al. 2016; Möller, Garro et al. 2016)).

Concerning the simulation time management, the SRFOM standard is focused on time stepped simulation providing support to three types of time management (Möller, Crues et al. 2016):

- HLA Time managed without pacing, fixed time steps;
- HLA Time managed with pacing federate, fixed time steps;
- HLA Time managed with real-time pacing federate, fixed time steps: (i) Strict/conservative - no frame overruns; (ii) Elastic with catch-up on Limited/Unlimited number of overruns.

To promote and support a-priori interoperability between SRFOM-based federates, the PDG defined a set of rules and guidelines for the execution management and control of an SRFOM-compliant Federation; in particular, the standard includes: (i) a set of *rules*; (ii) a template for a *Federation Execution Specific Federation Agreement (FESFA)*, which can be used to specify extra information including purpose of the Federation, Federation composition, time management policies, additional FOM modules, and technical configuration data; (iii) a *Federate Compliance Declaration (FCD)* template, which can be used to specify the information needed to integrate a federate into a SRFOM compliant Federation (Möller, Crues et al. 2016).

In order to develop a SRFOM-compliant Federation, development teams are encouraged to use and follow the IEEE 1730-2010 Distributed Simulation Engineering and Execution Process (DSEEP) (IEEE Std. 1730-2010). It provides a proven seven-step process, from establishing the goals and constraints for the federation to the final execution.

3 EXPERIENCES WITH THE SRFOM

In this section, the main and most interesting and relevant experiences, best practices and lessons learned from the exploitation of the SRFOM standard by the NASA Exploration Systems Simulations (NExSyS) team at NASA's Johnson Space Center (JSC), the Labs at Pitch Technologies, and the SMASH-Lab of the University of Calabria in developing compliant federates, are presented. They allowed to catch not only strengths but also weaknesses of the SRFOM standard so as to refine and improve it.

3.1 NASA experiences

This section of the paper provides a brief discussion of NASA's motivations for participating in the development of the Space Reference FOM and experience in using the standard. This includes a brief history of distributed simulation development in support of some of NASA's human space exploration efforts and some of the tools developed and used in that support.

Historically, NASA has engaged with both domestic commercial and international partners when planning and developing human rated space systems and missions. The ISS is a successful example of this. While human space exploration is a technically challenging endeavor by itself, these collaborations bring with them challenges beyond just the technical. Some of the non-technical challenges are political sensitivities, restrictions on proprietary data, and the protection of intellectual property. Collaborative distributed simulation is one technology that has successfully been used to address many of these technical and non-technical challenges.

One of NASA's early successes with distributed simulation was with the Japan Aerospace Exploration Agency (JAXA) and the H-II Transfer Vehicle (HTV) logistic supply vehicle for the International Space Station (ISS) (see Lauderdale, Crues et al. AIAA 2003; Lauderdale, Crues et al. SISO 2003). All NASA missions require significant training for flight controllers. The HTV logistic supply missions to the ISS are no exception. In this case, NASA worked with JAXA to develop a training simulation for the HTV and ISS flight controllers that involved a distributed simulation with components executing at JAXA's Tsukuba Space Center in Japan and at NASA's Johnson Space Center in Houston, Texas. Much of the research, development, and deployment for this project formed the knowledge base that would eventually be incorporated into the Space Reference FOM.

The ISS/HTV flight controller training simulation was a successful precursor to other NASA programs that benefited from HLA based distributed simulation (see Crues, Chung et al. 2007; Chung, Crues et al. 2007; Jennings, Blum et al. 2008). As NASA programs and their associated distributed simulations advanced, the developers observed a number of repeating challenges with developing, deploying and operating these simulations. In general, the developers observed that HLA provides a necessary simulation interoperability framework but is not sufficient by itself. There are some additional areas that need more formal agreement: simulation execution roles and responsibilities; fundamental data types and representations; initialization sequence and data dependencies; and execution control. Some of the specifics are described in more detail in these references: (Phillip, Crues 2005; Phillips, Dexter et al. 2007; Jackson, Murri et al. 2011). In general, this indicated the need for a more formal standard for interoperable space systems simulation. Specifically, this indicated a need for a Space Reference FOM.

NASA's Johnson Space Center (JSC) is one of NASA's lead centers for human space flight. JSC is the location of NASA's human space flight Mission Control Center (MCC) and the home NASA's astronauts. In addition to flight operations, JSC also supports important collaborative engineering design and development activities involving international partners. This includes development of distributed simulations for joint training and operations (e.g. the ISS/HTV simulation from above). Much of the core distributed simulation technology development, specifically associated with the Space Reference FOM, is done by the NASA Exploration Systems Simulations (NExSyS) team. While the NExSyS team itself formed in 2012, members of the team have simulation experience that reaches back into simulation support activities for both NASA's Space Shuttle and ISS programs. The NExSyS team's home is in the Simulation and Graphics Branch (ER7) at NASA JSC and they work with groups across the agency and internationally.

Experienced members of the NExSyS team are contributing to Space Reference FOM development and are members of the Product Development Group (PDG). They have been working with SISO and the PDG to incorporate some of the lessons learned in previous NASA distributed simulation projects. The NExSyS team is working with some of NASA's principal modeling and simulation tools to explore, develop and test the Space Reference FOM.

One of NASA's principal simulation development tools is the Trick Simulation Environment (see Trick 2019; Paddock, Lin et al. 2003). Trick provides a common simulation infrastructure used by many of NASA's space systems simulations. However, Trick itself is not a simulation, it aggregates constituent application specific models and provides a simulation framework for application specific simulations. In order to support distributed simulation, a simulation interoperability framework has been developed for Trick based simulations. The framework, called TrickHLA, is a Trick compatible implementation of HLA (see Crues, Lin et al. 2003; TrickHLA 2019). This, in conjunction with other space systems models, provides the simulation framework for implementing NASA federates for HLA based distributed simulations like the ISS/HTV proximity operations and capture flight control training simulation. NASA's NExSyS team has been modifying and using Trick and TrickHLA to help develop and test the Space Reference FOM. This includes adding Space Reference FOM support to TrickHLA.

These Space Reference FOM compliant tools will provide an important technology to support NASA's collaborations with domestic and international partners as we return to the Moon, explore Mars and move out into our solar system.

3.2 Pitch experiences

Pitch Technologies has been involved in the HLA community since 1995, both in the standardization efforts and the development of commercial tools that support the standard. The initial market was mainly defense and security, but already around 2000, the space community started to show interest. Pitch's infrastructure products were for example used in the NASA-JAXA federation for docking the HII-A Transfer Vehicle (HTV) with the ISS, as well as the ATV-ISS ground controller training system, distributed between Korolov, Bremen and Toulouse, developed by ESA and Astrium (Möller 2019).

Pitch was also a sponsor and provided software to the university outreach program Smackdown in 2010, later renamed Simulation Exploration Experience (Simulation Exploration Experience (SEE). 2019), where university teams developed and ran simulated space scenarios using HLA. These federations typically consisted of federates from five to ten university teams as well as sample federates provided by NASA. At this time Pitch had been involved in the development in several standards, like HLA Evolved (IEEE Std. 1516-2010) and Federation Development and Execution Process (FEDEP later renamed DSEEP) and were thus experienced in standards development (IEEE Std. 1730-2010). The Smackdown exercises triggered discussions about creating a standardized FOM for space simulation, leading up to forming the team that kicked off the standardization effort.

The Space FOM and SEE were also good opportunities to test Pitch's domain independent HLA tools. Pitch Visual OMT, a graphical object modeling tool, was used to develop the FOM modules for the Space FOM, as well as many different extensions for different SEE teams. The Pitch pRTI was used as the infrastructure for the simulation, which also lead to the addition of more views for inspecting scenario time during execution. Data was logged using Pitch Recorder. The code generator Pitch Developer Studio was used to generate code that made it easy to quickly adapt simulations to support the Space Reference FOM (Möller and Crues 2018).

In addition to the generic tools, Pitch developed two tools that are specific to the Space Reference FOM. The most important one is the Space Master, which can play the Master and Pacer role in a Space FOM federation. It manages the startup, initialization and execution phases of a federation execution and can pace the federation in real time and scaled real time. Another tool is the Space Monitor, that enables a user to monitor physical entities and reference frames in a federation execution.

It is very difficult to verify that a standard with distributed, concurrent processes is correct and complete by inspecting the standard itself. A proper testing methodology is needed. In this case it has proven very valuable to have three different teams (NASA, University of Calabria and Pitch) developing their own federates that implement the standard. During the testing phase, federates have been exchanged between the teams and different combinations have been tested. These tools have also been tested in the SEE federations.

The Space Reference FOM is particularly interesting for testing since it uses more of the powerful features of HLA than most defense federations, in particular the extensive use of time management and synchronization points. The Space Reference FOM also contains many clean and reusable solutions to problems that the defense community has been struggling with, such as multi-phase initialization, synchronized freeze, and hard real-time synchronization. It can be expected that other communities will reuse many design patterns from the Space Reference FOM.

3.3 UNICAL experiences

Since 2011, the Simulation Interoperability Standards Organization (SISO) in a joint cooperation with NASA and other industrial and research societies has been organizing a yearly event named *Simulation*

Exploration Experience (SEE) (Simulation Exploration Experience (SEE) 2019; Elfrey et al. 2011). The purpose of this international project is to provide a practical experience to undergraduate and postgraduate students so as to increase their abilities in M&S techniques and methods, especially, in Distributed Simulation (DS) systems compliant with the IEEE 1516-2010 standard (IEEE Std. 1516-2010).

The first draft of the SRFOM, version 0.1, has been successfully experimented during the 2017 edition of the SEE project where eleven universities took part: University of Alberta, University of Nebraska-Lincon, the Faculdade de Engenharia de Sorocaba FACENS, University of Calabria, University of Genoa, University of Bordeaux, University of Munich, University of Brunel, University of Liverpool, University of Jaipur, University of Bulgaria. In this edition, a moon settlement was simulated with a dangerous scenario involving an asteroid on collision course with the Moon. To avoid the asteroid impacts with the moon ground, a missile was launched to intercept and destroy it (Simulation Exploration Experience (SEE) 2019).

Starting from the experience gained from the SEE 2017 edition along with the case studies developed in industries in the aerospace domain such as NASA and Pitch (Pitch Technologies 2019), the SRFOM has been updated in order to improve the stability and reliability of compliant Federates. The updated draft of the SRFOM, version 0.2, was experimented in the 2018 edition of the SEE project in which ten universities participated either remotely or onsite in Sofia, Bulgaria, from 8th to 10th May 2018 to simulate a settlement on both moon and mars. The University of Brunel team implemented a simulation model, named *Excavator*, based on HLA and REPAST that is in charge of inspecting and collecting lunar regolith. The University of Gujray team developed a lunar rover, named *LNRV*, that is in charge to find minerals, located at different positions of the moon surface, through the use of a remote sensing technique. The team of Genoa University developed an asteroid defense system, named *IPHITOS*, composed of an asteroid detection system and a missile base. The team of the University of Central Florida contributed with six simulation models: (i) *Power Plant (POWR),* which is a large vehicle that produces power for all the component of the mission; (ii) *In-Site Resource Utilization Product Facility (IRPF)*, which is an in-site resource utilization designed as a large lander responsible for producing rocket fuel; (iii) *Swarmie (SRME),* which is a small rover with four wheels, a small arm for picking up small objects, a webcam and three infrared cameras; (iv) *Spent Regolith Maintenance Rover (SRMR),* which is a small rover with four wheels and a bucket, which contains the waste produced by lunar facilities; (v) *Regolith Advanced Surface System Operations Robot (RASR),* which is a vehicle with four wheels and two drum arms used to mine and store its payload. *RASR* was vertically symmetrical so as to be able to perform its actions if flipped upside down; and (iv) *Lunar Grid Federate (LUGF),* which is a simulation module that reproduces the lunar environment. The University of Bulgaria developed a *Habitat Thermal regulation System (HaTS)*, which is a live support system equipment for Mars habitat. It is a machine that regulates the temperature and other aspects of the living environment. The team of the Bulgarian Naval Academy created a moon landing port that allows landers to land on the lunar surface. The team of the Bordeaux University contributed with a lunar facility, named *Supply Depot*, that is used by astronauts to store supplies. The Munich University team developed a *Lunar Space Station (LSS)* located at Libration Point Two (LL_2). The team of FACENS developed a lunar habitat and some astronauts. The habitat provides to the astronauts housing, shelter, and a place to fulfill their basic needs, as well as communicate with the mission control center placed on earth. The "University of Calabria – Team 1", developed a drone called *DREDIS* for reconnaissance and exploration missions. The *SMASH-Lab* team of the University of Calabria provided, with the NASA team, support to the SEE teams in developing HLA federates compliant with the SRFOM (SISO Space Reference FOM (SRFOM) 2019; Möller, Crues 2016) also through the use of the *SEE HLA Starter Kit* software framework (Falcone et al. 2017). The framework was developed in 2014 by the *SMASH-Lab (System Modeling And Simulation Hub - Laboratory)* of the University of Calabria (Italy) working in cooperation with the *NASA JSC (Johnson Space Center)*, Houston (TX, USA) and it is released under the LGPL licence. The *SEE HLA Starter Kit* has been successfully experimented in the SEE project since the 2015 edition. The framework aims at easing the development of SEE Federates by providing: (i) a Java software framework, called *SKF*, for the implementation in Java of SEE Federates; (ii) a technical report that describes the *SKF*; (iii) a user guide that leads developers in using the framework; and (iv) some video-tutorials that present how to build both the structure and the behavior of a SEE Federate.

All the teams created for their Federates a 3D model to interact with *the Distributed Observer Network (DON) environment*, which is a real-time 3D visualization environment based on developed by the NASA team that tracks all the activities performed by the SEE Federates and displays updates on the 3D environment during the simulation execution through the DON Visualization Tool (DON-VT). Most of the SEE teams used the *SEE HLA Starter Kit* for developing their federates since it is SRFOM fully-compliant and provides a set of functionalities that make it easier for teams to use both the HLA and SRFOM standards (Falcone and Garro 2017).

The incoming 2019 edition will be held from 6th to 7th May 2019 in Cape Canaveral, Florida, USA, where 13 universities will participate in developing HLA federates compliant with the SRFOM version 0.3, which has been submitted for approval to SISO (SISO Space Reference FOM (SRFOM). 2019).

4 CONCLUSION

The paper presented the most interesting and relevant experiences, best practices and lessons learned from the exploitation of the ongoing Space Reference FOM standard (SRFOM) by the NExSyS team at NASA's Johnson Space Center (JSC), the Labs at Pitch Technologies and the SMASH-Lab of the University of Calabria in developing compliant federates.

Different experimentations have been performed, also in the context of the SEE project (Simulation Exploration Experience (SEE) 2019), that allowed the SRFOM PDG to get a deeper understand of the strengths and also the weaknesses of the SRFOM standard. Main issues raised during these experimentations have been considered to improve the SRFOM standard that is currently under evaluation by SISO; indeed, it is in the *Product Balloting* phase under evaluation by the member of the balloting group; in the meanwhile the dissemination of preliminary results in premiere related international workshops and conferences is carried out so as to get feedback from the community. In addition, the results, deriving from the SRFOM experimentation activities, have been brought to the attention of the standardization committee of the new HLA 4.0 standard, which also includes some members of the SRFOM PDG, so as to contribute to the definition of the incoming release of the HLA standard.

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