Nationaal Lucht- en Ruimtevaartlaboratorium

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Deploying network real-time simulation, putting the virtual enterprise to work

Some aerospace experience

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Summary

Aerospace products are typically high-tech, high quality and low volume. They are produced by specialised geographically dispersed companies. The production is dominated by a large amount of engineering. In the engineering phase each company makes extensive use of real-time simulation for its own (sub) systems. At the same time the aerospace industry is becoming more competitive. This way of working combined with the business realities provides an opportunity to deploy the virtual enterprise concept in the aerospace domain. This paper focuses on the virtual enterprise as realised by networking existing real-time simulators. Major applications of networked real-time simulation are training, mission planning and networked R&D. Each of these applications is illustrated with an example from a different domain. Networked simulations require exercise management for which this paper presents a re-usable implementation based on international standards. Our experience, consolidated in the SmartFED tool, shows that the virtual enterprise concept as embodied in networked simulation provides benefits like increased quality and reduced time-to-market of a product.

Contents

(24 pages in total)

1 Introduction

The aerospace industry is becoming more competitive so it is adopting the global trend towards the virtual enterprise business model to realise a reduction of cost and of time-to-market while increasing product quality. These objectives are reflected in NASA's 'faster, better, cheaper' development paradigm. For a discussion of its relevance for other aerospace applications see [1]. Aerospace products typically are high-tech, low volume products that are subject to severe environmental conditions, necessitating compliance to rigorous quality standards. This results in a substantial engineering process, including extensive verification and validation activities. For critical products, verification and validation can be the most costly realisation activity. In the engineering phase each company has to make extensive use of real-time simulation for its own (sub) systems. Usually many geographically dispersed companies contribute to the final product. Traditionally every company produces its own real-time simulator for its subsystems, often containing a lot of proprietary information. By necessity each company has to simulate its product environment as well. These characteristics of the aerospace industry provide a good opportunity to deploy the concept of the virtual enterprise from the Enterprise Application Integration (EAI) domain, focussing on the large engineering component.

This paper describes an approach to EAI based on coupling various existing real-time simulators into a multi-site networked simulation, thereby crossing the boundaries of the participating organisations. Each contributing simulator is considered an autonomous entity. Issues like programming language, legacy systems, and business concerns like confidentiality of the proprietary information incorporated within the simulator have to be shielded from the networked simulation they participate in. The only requirement on each participating simulator is that the information it is willing to share can be described and accessed in a uniform way by the other simulators.

The networked simulation results in a synthetic environment (SE) that can be used for the following applications

- training or e-learning, in which a group of people (the trainees) are subject to a curriculum containing a fixed set of scenarios,
- mission planning, in which a group of operational experts (e.g. cosmonauts) plans or optimises its task, by simulating the mission, analysing the result and retrying using a modified scenario,
- networked research and development, in which a group of engineers create or improve a product or service by also modifying the characteristics of the participating real-time simulators or even the participating entities of the networked simulation.

Each application of the networked simulation is illustrated by an example of the EAI concept, either realised or being worked on. In addition some of the enabling technology is explained. Note that all applications of the synthetic environment entail humans, hence the requirement for their real-time behaviour. Each simulator may contain actual hardware (sub) systems, reinforcing the need for their real-time behaviour.

The small volume of the aerospace market with respect to other markets implies that Commercial Off-The-Shelf (COTS) or Modified Off-The-Shelf (MOTS) products and standards have to be used wherever possible to contain costs, project risk and time-to-market. As a result our approach to networked simulation is based on existing standards. The next section describes two standards, followed by a section on the simulation development process. Networked simulation requires amongst others managing the real-time execution, which together with its preparatory integration activities is commonly referred to as exercise management. This paper presents SmartFED, our re-usable implementation, consisting of three components. The section on the SmartFED Federation Manager is illustrated with a training example from the military domain. The Federation Monitor is described using a mission planning application from the space domain. The section on the last component, Scenario Definition and Execution Manager contains a networked research and development example from the air transport domain.

2 Simulation standards

Two standards are often used to connect geographically dispersed real-time simulators: Distributed interactive Simulation (DIS) [2], [3], [4], [5], [6], [7] and High Level Architecture (HLA) [8], [9], [10]. The military Defence Modelling and Simulation Office (DMSO) has initiated both standards to support application-to-application integration. Usually the simulators belong to different organisations, resulting in business-to-business integration [11]. Using these standards and the accompanying products thus complies with the COTS/MOTS philosophy. The older DIS standard only defines the Protocol Data Units (PDU's). During the simulation every PDU is broadcast to all participating simulators. Due to the many pre-defined data types this approach leads to quick results. This comes at the expense of inflexibility of the exchanged data and inefficient network bandwidth utilisation, which can be scarce in the envisaged aerospace applications. To check whether a data link to a participating simulator remains operational, regular 'heart-beat' PDU's are send when all objects supplied by that simulator happen to remain constant for a certain period, adding to the communication load.

Based on the experience with DIS, HLA takes a different approach. An architecture is provided that supports component based simulation, with each real-time simulator being a component.

On each simulator site the so-called Run Time Infrastructure (HLA-RTI) takes care of all communication. DMSO supplies an HLA-RTI and commercial versions connecting various platforms are also available. This guarantees HLA support for many hardware platforms, many operating systems with several language bindings available, providing the important characteristic of heterogeneous network support. The COTS approach efficiently ensures that new hardware and software platforms will be supported, whenever they become available.

HLA allows each participating entity, e.g. a simulator or federate in HLA terminology, to define the set of attributes of (selected) objects it will make available to the other networked simulators and which objects will remain private and hence inaccessible for the other simulators. The Simulation Object Model (SOM) describes all data needed by and provided by a real-time simulator. All data published in or subscribed to in the entire networked simulation, or federation in HLA parlance, is contained in the Federation Object Model (FOM). As long as the FOM vocabulary contains all data subscribed to by a simulator, that simulator can participate in the federation. When another federate provides the same Simulation Object Model (e.g. an updated, faster or more accurate version), it can replace the original simulator without affecting the entire networked simulation. This feature greatly improves the re-use of both simulators and networked simulations. The features of HLA cause a steeper learning curve with respect to DIS.

The HLA-RTI takes care to send only those data into which a simulator has declared its interest, thus optimising network bandwidth utilisation. To compensate for varying network delays, the HLA-RTI provides a ‘dead reckoning’ mechanism which extrapolates the data, until new information becomes available. This feature further reduces the amount of custom code to be produced and maintained. Due to these advantages, HLA has been chosen for all work described in this paper. Our DIS experience confirms the general characteristics provided above. More information on the relative merits of DIS and HLA is provided in [12].

3 Simulation development process

As the process of developing a networked HLA simulation remains quite complicated, DMSO has developed the 6-step Federation Development and Execution Process (FEDEP) process [13], depicted in figure 1.

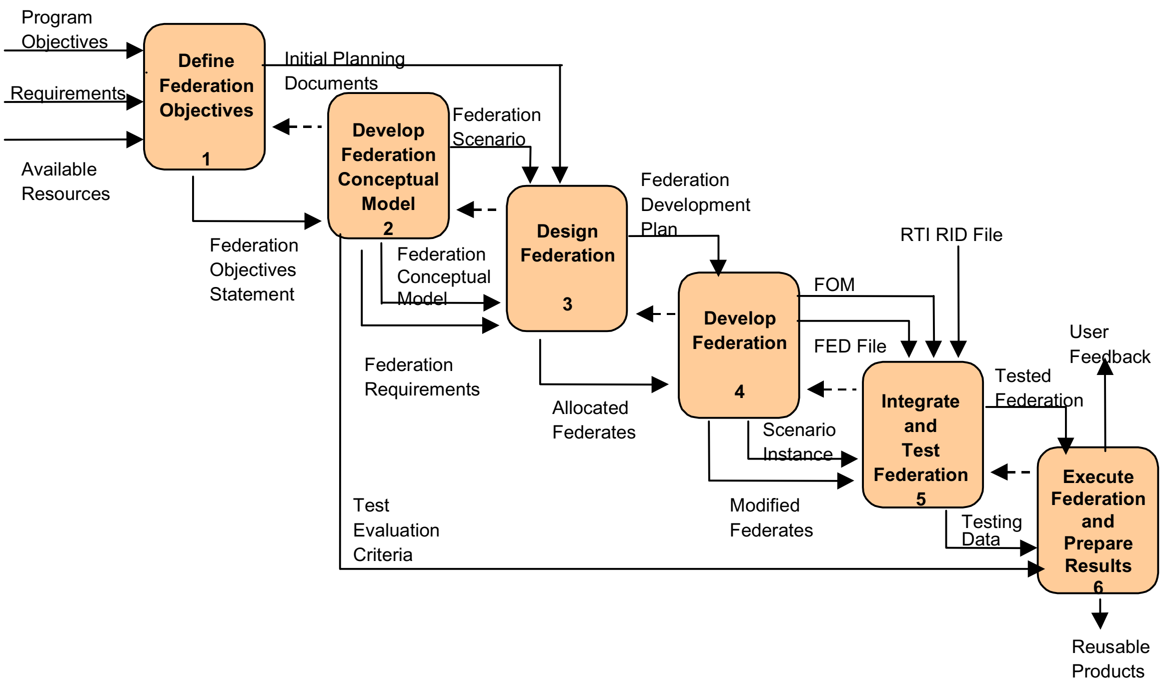

Figure 1 Federation Development and Execution Process (FEDEP) process

- **Step 1: Define Federation Objectives.** The federation user and federation development team define and agree on a set of objectives and document what must be accomplished to achieve those objectives,
- **Step 2: Develop Federation Conceptual Model**. Based on the characteristics of the problem space, an appropriate representation of the real world domain is developed,
- **Step 3: Design Federation**. Federation participants (federates) are determined and required functions are allocated to the federates,
- **Step 4: Develop Federation**. The Federation Object Model (FOM) is developed, federate agreements on consistent data bases / algorithms are established and modifications to federates are implemented (as required),
- **Step 5: Integrate and Test Federation**. All necessary federation implementation activities are performed, and testing is conducted to ensure that interoperability requirements are being met,

- **Step 6: Execute Federation and Prepare Results**. The federation is executed, outputs are generated, and results are provided.

After several iterations by the user community the FEDEP process version 1.5, is now sufficiently stable to be subjected to the standardisation process.

4 Exercise management

The work on exercise management described in this paper concentrates on FEDEP steps 5 and 6. The resulting tool, Scenario Manager for Real-time Federation Directing (SmartFED) [14], [15] has three main functions, each implemented in its own independent component:

- **Federation Management**, to control the execution state of all participating simulators in the entire federation,
- **Federation Monitoring**, to allow a user (e.g. the supervisor / experiment leader or the trainer) to monitor any object in the networked simulation on any location,
- **Scenario Definition and Execution Management,** the definition part supports the off-line definition of the participating simulators initial conditions and the definition of events like the generation of failures. Once the simulation is being executed the execution part will activate the events at the predefined times or conditions or on operator request.

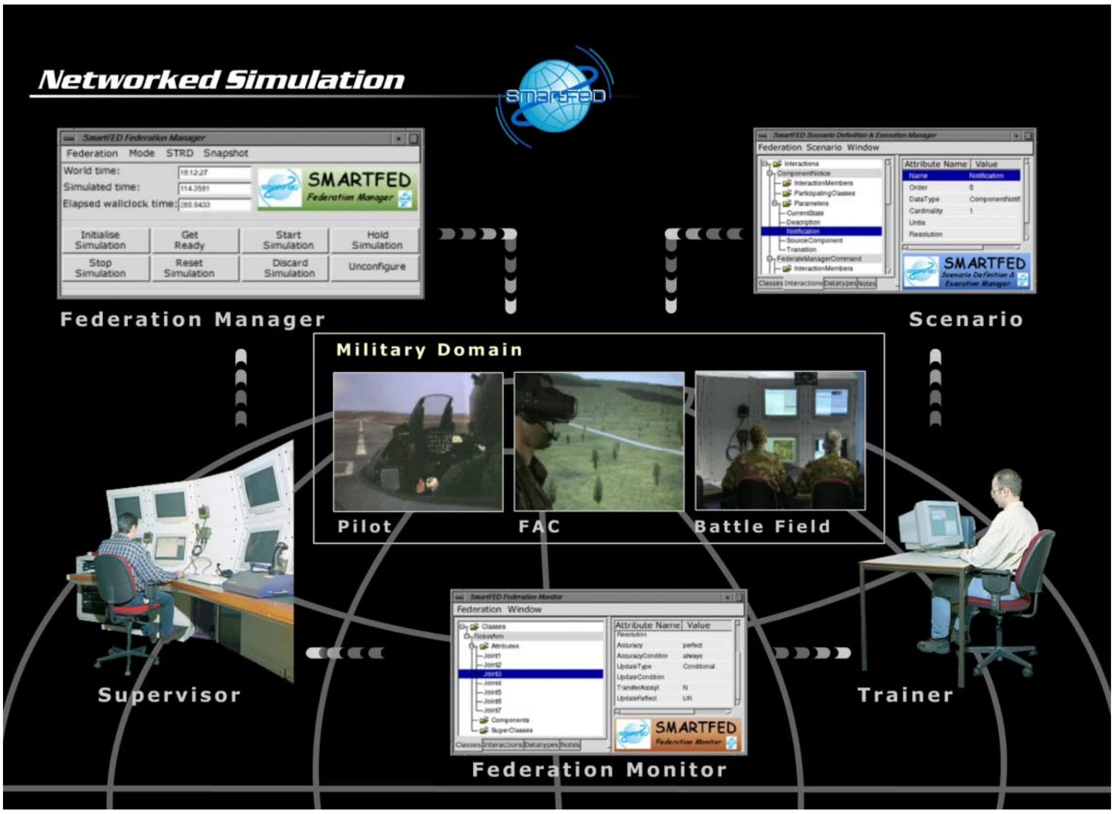

Figure 2 Training example showing SmartFED components

Figure 2 depicts a networked simulation and the SmartFED components for a training application. The next sections will elaborate each function of exercise management and SmartFED's implementation of it, based on different networked simulation applications (training, mission planning and networked R&D) and illustrated by different networked simulation example.

5 Federation Management

Federation Management is illustrated by a networked training example from the military domain. A Forward Air Controller (FAC) is an observer that directs a fighter aircraft to its target. To train the combination of FAC and pilot, while preserving the environment and reducing aircraft wear and cost, networked real-time simulations are used. Stand-alone real-time simulators are available for the fighter aircraft [16], [17] the FAC and the encompassing battlefield. Figure 2 depicts the networked simulation and the SmartFED components involved.

The Federation Manager provides central control over the networked real-time simulation. The supervisor (sometimes called experiment leader) operates the Federation Manager. The supervisor decides when certain commands are sent to the federation. As depicted in Figure 2 the supervisor can react on signals displayed by the Federation Monitor, which is discussed in the next section. The person using the Federation Manager can also use a Federation Monitor, but this is not necessary. The Federation Manager is the only mandatory SmartFED component. Due to the centralised control only one copy can be active in a networked simulation. The Federation Manager may be located at any simulation site or even on another geographic site.

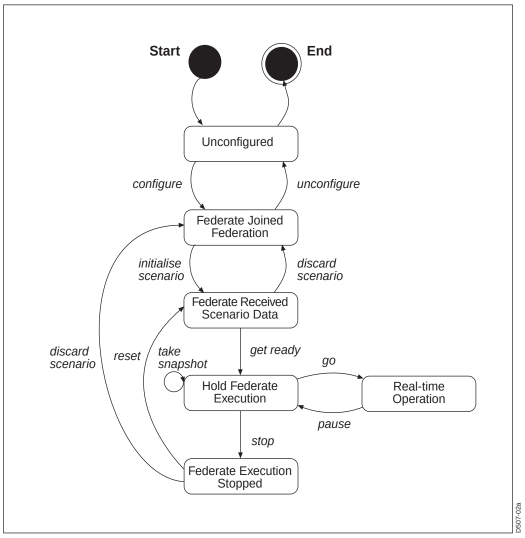

Figure 3. Sample federation state-transition diagram

A general state-transition diagram has been designed, depicted in figure 3. Each of the three federates must comply, from an exercise management point-of-view, with this state-transition diagram. However, federates may well possess an internal state-transition diagram that differs from the one depicted in figure 3. This is actually often the case for legacy simulators, like the legacy battlefield and FAC simulators of this example. The Federation Manager sends state-transition commands to all federates. Federates reply with success or failure notifications to the Federation Manager.

The Federation Manager subscribes to some federate data and federation data provided by HLA's Management Object Model (MOM) in order to know the states of each federate present in the federation. The Federation Manager may only send a state-transition to the federation when all federates are in the same state, although for test purposes a 'free-running' mode is supplied. State-transition commands are made available to the supervisor by means of a graphical user interface, depicted in the large window in Figure 4. The smaller window displays the active federates.

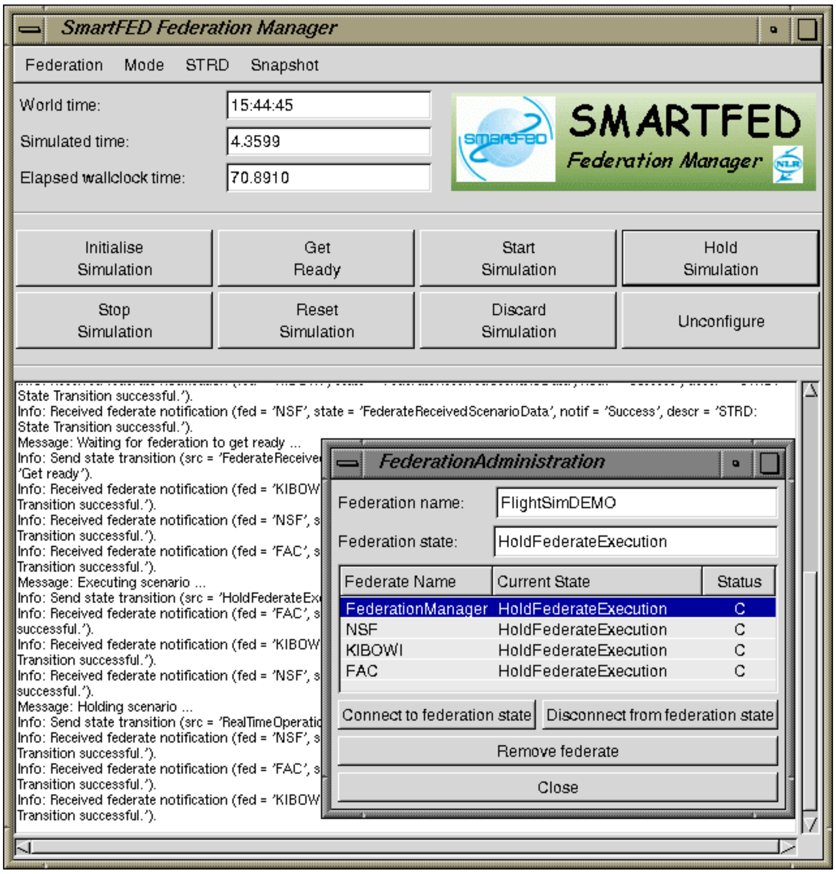

Figure 4 SmartFED Federation Manager sample window

A dedicated message field is available to notify the supervisor of warnings or errors that occur during the federation execution, for instance when a federate loses the network connection with the rest of the federation.

The Federation Manager supports the initiation of snapshots by forwarding the snapshot invitation to the HLA RTI of the participating federates. A snapshot contains a dump of the entire internal state of a federate. Of course this is only possible if a federate is able to take a snapshot. In order to preserve the real-time nature of the simulation, snapshots can be only generated when a federate is in the 'Hold Federate Execution' state. The same holds for restoring a federate by means of a previously created snapshot.

During 'After Action Reviews', parts of the scenario can be replayed and analysed. Registering 'bookmarks' during scenario execution can facilitate such reviews as they serve as easy to find starting points for the review. The supervisor can add a bookmark at any point in time during the scenario run that might be of interest to the evaluation of the scenario afterwards.

The generic state-transition diagram used allowed all three proprietary simulators of the training simulation to comply with it. This confirms the general nature and reusability of this SmartFED component. For simulation control the communication needs of SmartFED's Federation Manager were modest. The additional load on the standard ISDN (Integrated Services Digital Network) lines used was negligible. The HLA interface description of SmartFED itself consisted of around only 100 lines of non-comment HLA-RTI (Run Time Interface) definition.

The networked simulation allowed training of the FAC-pilot combination outside some restricted military aeras, which was impossible before, thereby increasing their team capabilities while reducing the environmental impact and aircraft wear and cost.

6 Federation Monitor

To explain the Federation Monitor an example of mission planning from the space domain is selected, illustrated in figure 5. The International Space Station (ISS) contains the European Robotic Arm (ERA). Both to train the cosmonauts as well as to plan missions with ERA the Mission Preparation and Training Equipment (MPTE) real-time simulator has been realised. For more information on MPTE see [18], [19], [20]. MPTE contains a simple model of the 'payload' it handles. Other ISS partners possess much better real-time simulators of their subsystems, thus providing the prerequisites for a EAI approach supported by networked simulation.

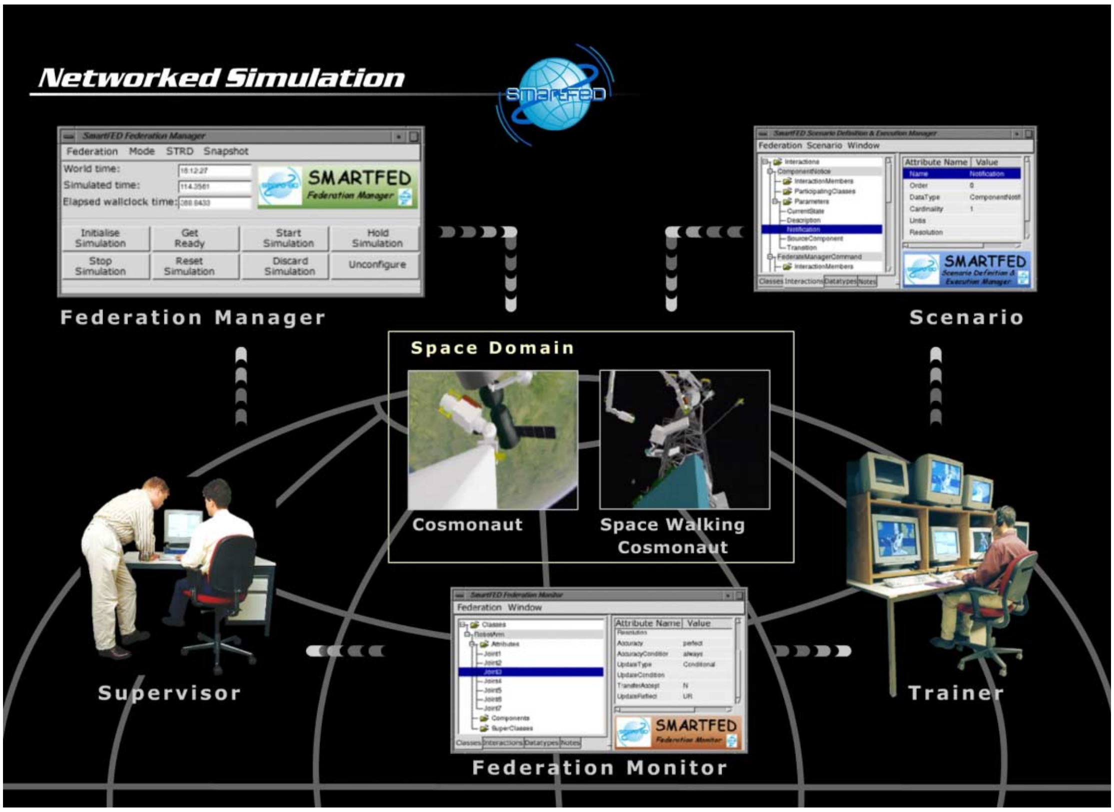

Figure 5 SmartFED example for mission planning

The Federation Monitor provides its user with a view of the entire federation. This includes both a graphical overview showing the positions of the simulated entities with respect to each other and a textual view of the federation containing detailed information of the participating federates. The Federation Monitor is an optional component. The networked simulation can run without it. As the Federation Monitor can not change the values of the objects it monitors, as many Federation Monitors can run simultaneously as required, e.g. one Federation Monitor per simulation site.

The Federation Object Model (FOM) is composed of the collection of published federate data and interaction data within the networked simulation. The FOM, which uses a Backus-Naur Form notation [21], is used as the basis for the implementation of the Federation Monitor. The Federation Monitor reads the FOM file to enable its user to browse graphically through the FOM. With this browser the user can subscribe and unsubscribe to federate data and federate interactions at will during the simulation execution. Figure 6 shows the Federation Monitor.

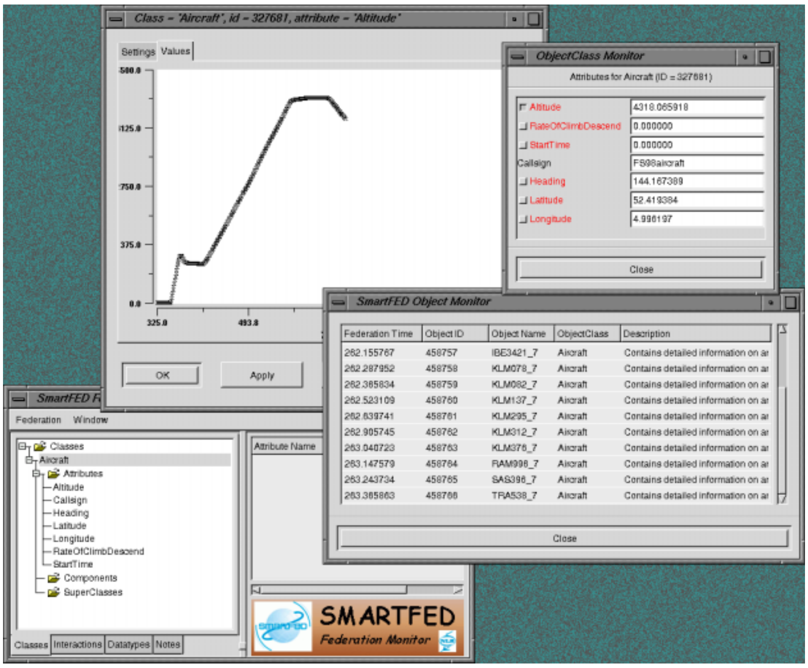

Figure 6 SmartFED Federation Monitor

When new data is published by a federate, it will appear as an icon in the Federation Monitor using the information contained in the FOM. Detailed information on federate data and its attributes can be displayed. The Federation Monitor will subscribe to federate interactions and display those incoming events that the user is interested in. A separate interaction view provides the user with an overview of all interactions that have occurred during the federation execution. For each interaction the detailed information on its parameters is available.
Since in principle, the Federation Monitor can subscribe to all data that are made available in the federation i.e. the entire FOM, network congestion may occur when a user actually does so. The level of accuracy of the monitoring depends on the network load and may decrease as the number of monitored objects increases, see also [22]. It is expected that this part of SmartFED will be able to exploit the increased bandwidth and reduced latency capabilities of the upcoming broadband networks.

In order to promote re-use, not only for simulator components, but also within SmartFED, the Federation Monitor is based on some extensions to the Scenario Definition and Execution Manager. As the Federation Monitor can display all standard FOM data types including composite types and arrays, hardly any modifications were needed for the various networked simulations in which it has been deployed. This experience substantiates the significant gains in costs and time-to-market made possible by re-using SmartFED components.

This networked simulation provides an increased fidelity of the simulation and hence an improved quality of the mission planning.

In a separate exercise ESA has coupled real-time simulators based on HLA standards. In this case no general exercise management tools, like SmartFEd have been used. In their report [23] they estimate that for the large Autonomous Transfer Vehicle (ATV) project, the networked simulation approach is feasible and would result in reduced costs and a 20% reduction in time-to-market.

7 Scenario Definition and Execution Manager

The Scenario Definition and Execution Manager is illustrated using an example of networked research and development from the air transport domain. Currently congestion at airfields is growing rapidly. In order to reduce air traffic congestion several air traffic management tools are being developed, amongst which are an arrival manager and a departure manager, both of which are the subject of the networked research. To assess whether the research versions of these tools co-operate well, a scenario is conceived in which an incoming flight is delayed. In order for the transfer passengers to catch their connecting flight, this delay implies a re-rescheduling of the departing aircraft. All of this has to be accomplished with minimal impact on the overall air traffic system capacity. A networked simulation can be made, consisting of an approach simulator containing the arrival manger [24], [25], a flight simulator for the late aircraft [26] and an airfield simulator including the departure manager [27]. Figure 7 shows the resulting networked simulation.

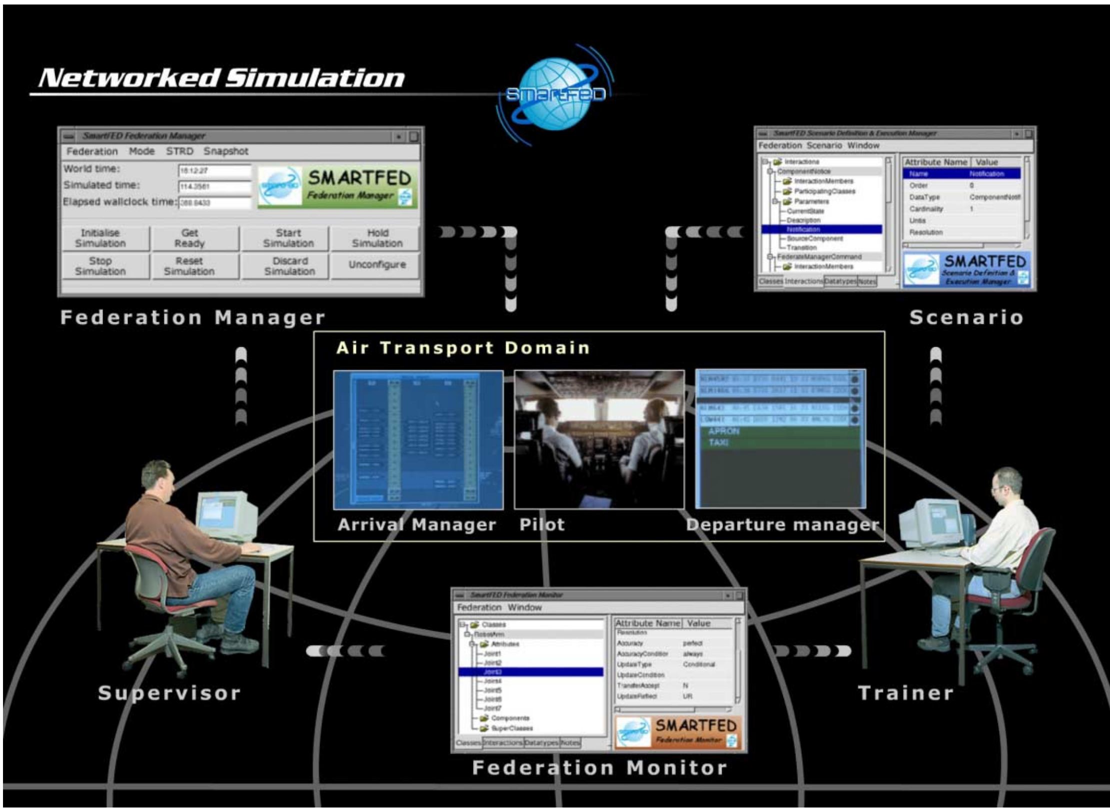

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Figure 7 SmartFED example for networked R&D

During the off-line scenario preparation of the networked simulation SmartFED's Scenario Definition component is used to specify a scenario by the supervisor, trainer or researchers involved. The scenario is defined for a particular configuration of that federation. A scenario consists of the following parts:

- federation composition: defines the federation name and which federates in the federation participate in the specific scenario,
- environmental conditions definition: the geographical environment in which the federation is operating (e.g. European airspace) and the meteorological conditions (e.g. fog),
- initial condition definition for each federate: the initial values of the federates data attributes (e.g. the aircraft position, altitude, speed, estimated arrival time, estimated time of departure, etc),
- stimuli definition during scenario execution: which events must occur at what time during the scenario (e.g. the delayed arrival or the reschedule departure request).

Figure 8 shows an example of a scenario definition file.

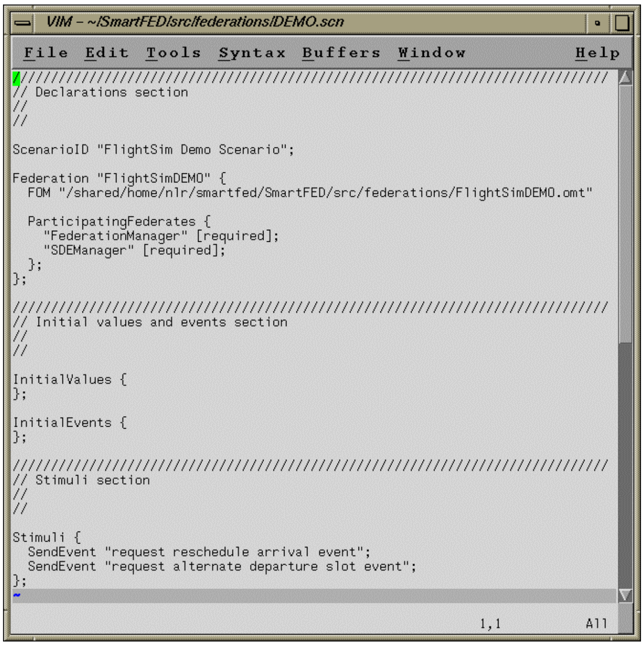

Figure 8 Networked simulation scenario

During the networked simulation, the Scenario Execution component reads the predefined scenario. It sends the initial conditions to the federation when the Federation Manager generates the ‘initialise scenario’ command (see figure 3). During the ‘Real-time Operation’ state (figure 3) the Scenario Execution component will send the events to the federation at the times specified in the scenario or on operator request. Figure 9 shows an example of the Graphical User Interface (GUI). The Scenario Definition and Execution Manager is an optional component, which has been omitted in some (training) simulations.

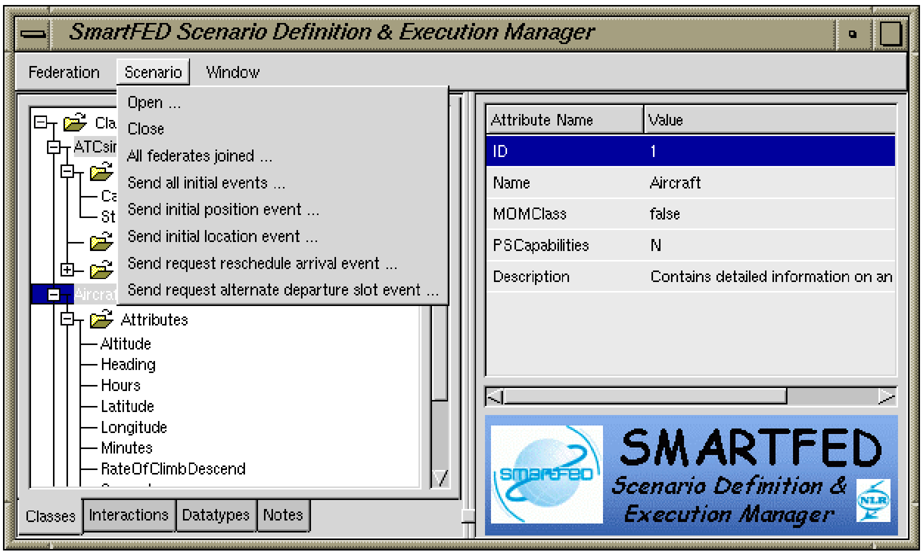

Figure 9 SmartFED Scenario Definition and Execution Manager

In the Air Traffic Management domain, real-time simulations are a necessary step between a research idea and a costly multi-national implementation. Networked research and development will allow to assess certain tool combinations. Some ideas can only be evaluated by exposing the Air Traffic Controllers to a real-time simulation [24]. This EAI approach facilitates a reduction in the (too) long time-to-market typical in safety conscious industries.
The implementation of the Scenario Definition and Execution Manager is based on the implementation of the Federation Monitor. While the Federation Monitor allows the user only to watch the federate data and interactions, Scenario Definition allows the user to set the values of federate data available in the FOM and generate interactions during the scenario definition phase.

For all three SmartFED components, the Graphical User Interface, see figures 4, 6 and 9, is based on the open source GTK+ toolkit. This package preserves SmartFED's platform independence acquired by choosing HLA. The experience with the various platforms used in the various federations in which SmartFED has been deployed [14], [15] confirms its support for heterogeneous networks.

In the first and last example of networked simulation it was observed that the construction of a synthetic environment, which means ensuring that each participating simulator uses a consistent view of the simulated environment e.g. the location of a tree on a hill, is quite labour intensive. No tools are known to expedite this process. In line with the ponieering role of the military in networked simulation, the Western European Armament Group (WEAG) initiated a substantial project to improve on this part of networked simulation [28].

8 Conclusions

Organisations are increasingly participating in a virtual enterprise, an example of EAI, to remain competitive. In the aerospace market this has resulted from the 'faster, better, cheaper' development paradigm. With the large amount of engineering typical in aerospace products, applying the EAI concept has translated into combining proprietary real-time simulators into networked simulations. These networked simulations can be deployed for training, mission planning and networked research and development. The three examples discussed in this paper illustrate the success of networked simulation. Networked simulation can provide training capabilities where this was impossible before. In the mission planning example it increased the fidelity of the simulation and hence the quality of the product (mission). In the networked research and development case it will allow to assess certain tools as well as reduce the time-to-market, thus achieving the objectives for the application areas.

The High Level Architecture (HLA) standard, which originated in the military world, has been applied successfully, supporting heterogeneous networks and providing many language bindings by harnessing the power of generic COTS tools for a specific market. The SmartFED approach to exercise management allows re-using its three components, Federation Management, Federation Monitor and Scenario Definition and Execution Management in different application domains.

The construction of a synthetic environment remains labour intensive. To increase the usability of networked simulation, work is being initiated to reduce the amount of resources needed for this task.

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10 Abbreviations and Acronyms

ATV	Autonomous Transfer Vehicle
COTS	Commercial Of-The-Shelf
DIS	Distributed interactive Simulation
HLA	High Level Architecture
DMSO	Defence Modelling and Simulation Office
EAI	Enterprise Application Integration
ERA	European Robotic Arm
FAC	Forward Air Controller
FEDEP	Federation Development and Execution Process
FOM	Federation Object Model
GUI	Graphical User Interface
ISS	International Space Station
MOM	Management Object Model
MOTS	Modified Of-The-Shelf
MPTE	Mission Preparation and Training Equipment
PDU	Protocol Data Units
RTI	(HLA) Run Time Infrastructure
SE	Synthetic Environment
SmartFED	Scenario Manager for Real-time Federation Directing
SOM	Simulation Object Model
WEAG	Western European Armament Group