System Engineering and Integration Aspects of a Multi-National HLA Federation Development

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ABSTRACT: *The NATO/PfP Interoperability and Re-use Study, NIREUS, is a twelve-nation project to apply the High Level Architecture (HLA) to investigate multinational distributed simulation for system design and acquisition. The NIREUS test case concerns distributed simulation of Vertical Take-Off and Landing (VTOL) air vehicles landing on ships, initially focusing on Maritime Unmanned Air Vehicles (MUAVs) but also addressing conventional manned aircraft. This problem incorporates daunting physics and military operations issues, which are dependent on understanding system interoperability between the ship, air vehicle, air vehicle control, and the landing system. Sufficient understanding of interoperability early in the system design process can be leveraged to optimize the ship/aircraft design in consideration of landing operations. The results of this experience-based study will be applied to the realm of Simulation Based Design and Virtual Prototyping, potentially leading to NATO-wide standards.*

This is an engineering-level federation development that involves federate developers from six different countries, where the majority of the federates are themselves being built by multi-national partnerships. The federation contains both new federates and legacy codes with new HLA interfaces, and will be a working federation in September 2001. Design for re-use is paramount. The work involves subject matter experts on physics-based models from the three domains of ships, air vehicles, and landing systems. Also mixed in are a group of simulation technology experts. FEDEP execution has been interesting and challenging in this multi-national and cross-domain environment. This paper discusses the various system engineering and integration aspects encountered thus far during NIREUS development, including: team formation, conceptual modeling, FOM production, and integration planning.

1. Introduction

The NATO Naval Armaments Group on Ship Design established a Specialist Team on Simulation Based Design and Virtual Prototyping (ST-SBDVP) to share information on the benefits, risks, and costs of instituting the technologies and processes of SBDVP applied to the acquisition of naval warships. During the course of the ST-SBDVP efforts a multi-nation simulation interoperability study was developed, called NIREUS (NATO/PfP Interoperability and REUse Study).

The NIREUS test case concerns distributed simulation of the Vertical Take-Off and Landing (VTOL) of manned and unmanned air vehicles landing on ships. Air vehicles will frequently encounter a hostile aerodynamic environment in the vicinity of an aft located flight deck, arising from the airflow over the moving ship superstructure and the downwash induced by the air vehicle. These conditions will potentially reduce thrust margins during landing and take-off, thus impacting safety of operation. To reduce this hazard, NIREUS intends to predict the main flow features that constitute the hostile environment and then minimize them by, for example, changing the ship superstructure design. Similarly, NIREUS is investigating the levels of performance that can be achieved by alternative methods for landing Maritime Unmanned Air Vehicles (MUAVs) automatically on a warship of moderate size. The problem space is sufficiently complex and challenging to exercise most aspects of reusability, interoperability, and collaboration. Modularity will ensure that different ships, air vehicles, and environmental models may be plugged in.

The first NIREUS efforts are aimed at a demonstration federation available in September 2001. The federation will consist of federates provided by multiple participating nations. An important objective is to gain insight in the development process of such a multi-national federation.

This paper describes the systems engineering and integration aspects of the development of the multi-national NIREUS demonstration federation development. Section 2 outlines the organization of the NIREUS team. The development of the federation follows the FEDEP process, as sketched in Section 3. Sections 4 through 7 describe our experiences during the steps of the FEDEP.

2. NIREUS Team Formation

NIREUS efforts are supervised by a Study Executive Steering Group (SESG) which reports directly to the ST-SBDVP. The actual work of constructing the NIREUS federation is conducted by four multinational teams, each provided with specific responsibilities and tagged with an arbitrary color, as given in Figure 1. Each team has a designated country responsible for team leadership, with a second country as alternate. Until now, the colored teams report to the SESG via the respective team leaders. Currently, in the phase of NIREUS Federation development, the team leaders report to the International Project-team Leader, chosen by the colored teams, which is made responsible by the SESG for reporting the progress of the demonstration to the SESG.

The conglomeration of NIREUS colored teams has come to be known as the “Rainbow Team”. The Blue Team is generally responsible for M&S associated with the ship itself. The Yellow Team is generally responsible for M&S associated with the air vehicle and air wakes. The Green Team is generally responsible for ship-air vehicle systems interoperability issues, such as landing algorithms, tracking sensors, and air vehicle touch down/tie down analysis.

The red team is generally responsible for simulation interoperability issues, such as federation integration, visualization, and coordination of the Federation Object Model (FOM). The red team acts as the overall systems engineer for NIREUS federation development.

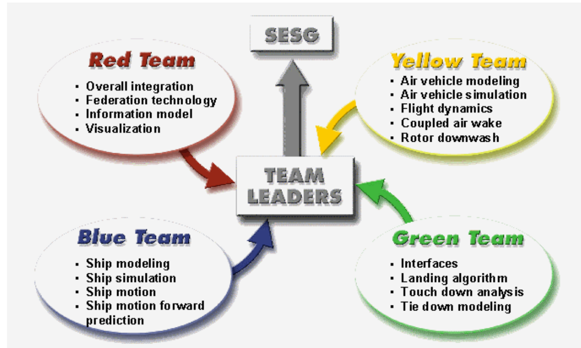

Figure 1 Initial NIREUS team organization

3. NIREUS Federation

The NIREUS Federation for the 2001 demonstration Federation is presented in Figure 2.

The NIREUS Federates are (in no particular order):

- Ship Motion Federate; this federate will supply the “real” ship motions, computed by a Ship Motion Module that can operate in both frequency and time domain to allow for maximum reuse of this federate for simulating different ship models.
- Ship INS (Inertial Navigation System) Federate; this federate transforms the “real” ship motions into “measured” ship motions that will be used by the MUAV Sensor Tracking Systems on board of the ship.
- Ship Motion Forward Prediction Federate; this federate predicts or designates a “safe” period in ship motion suitable for landing of the MUAV, based on measured ship motions and input characteristics for the MUAV and the ship.
- Air Vehicle Federate; this federate simulates the MUAV motions, control systems, onboard sensors and descent path planning. It generates the “real” air vehicle motions for use by the tracking sensors on board of the ship. It also generates “measured” air vehicle motions that will be used internally for simulating path planning of the MUAV to reach a ‘predicted landing position’.
- Air Wake Federate; this federate provides the air vehicle federate with airflow data, using a validated air-wake model of the particular ship. The air flow data will not be calculated in real-time but taken from a look-up table.
- Tracking Sensor Federate; this federate simulates a simple sensor measurement model for the “tracked” motion of the air vehicle relative to the ship during approach and landing.
- Landing Algorithm Federate; this federate simulates the landing control system, assumed to be on board of the ship. The landing control system uses the “tracked” MUAV position and “measured” ship

positions to determine where the MUAV will land in a certain period of time. This 'predicted landing position' is communicated to the MUAV (in reality this could be done through a communication Up-Link).

- Touchdown Dynamics Federate; this federate evaluates the moments and forces of the air vehicle undercarriage when it makes contact with the deck of the ship in order to determine whether the landing is successful.
- Federation & Scenario Management Federate; this federate should send initialization data to the federates, synchronize the federation execution, and, if possible, allow for deterministic multiple simulation runs within a federation execution (cf. Monte-Carlo simulation). In NIREUS, an existing HLA tool is re-used: the Virtual Ship Execution Manager (VSEM), developed in the Virtual Ship Project [4].
- Visualization Federate; this federate visualizes the virtual environment for the purpose of demonstration of the NIREUS Federation. A Commercial-Of-The-Shelf visualization tool will be used as the basis.
- Data Collection Federate; all data that is exchanged between the federates (FOM data) will be logged by this federate for post-processing activities. An existing (COTS) HLA Logger will be used (DCT).

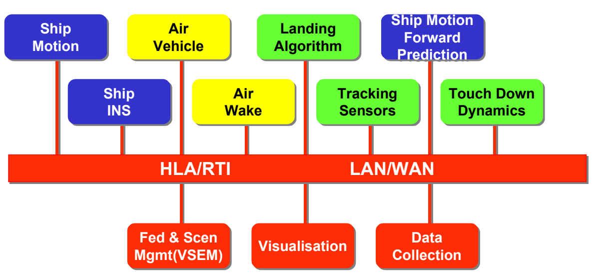

Figure 2 NIREUS Demonstration Federation Design

4. Federation Development and Execution Process (FEDEP)

The NIREUS Federation is being developed according to the Federation Development and Execution process (FEDEP) [3]. A tailored version of the FEDEP checklist was written initially to see how the project progressed on specific issues, and to identify new issues that had to be discussed and resolved.

The following documentation is currently being used:

1. *The NIREUS Milestone I Report*. This document [3] provides the results of FEDEP step 1, 2, and 3. It describes the statement of 'Federation Objectives', 'Scenario Requirements', 'Federation Conceptual Model' and 'Federation Requirements'. In addition, it describes the NIREUS Federation Design for the 2001 interim demonstration.
2. *Federation Design and Development Documentation.* This documentation provides details for FEDEP steps 3 and 4, from the perspective of the overall federation. It contains separate documents describing specific simulation issues for the purpose of discussion, clarification of concepts, and a statement of agreements within the NIREUS Federation:
   2.1. NIREUS FOM (Federation Object Model);
   2.2. Federation Management;
   2.3. Time Management;
   2.4. Usage of Coordinate Systems.
3. *Federation Integration and Test Document.* This document shall provide documentation for FEDEP step 5. It describes the NIREUS Test Harness that is used by the federate developers to test NIREUS Federates. The Test Harness is primarily used to test HLA interfaces and the Test Federates do not have physical functional behavior.
4. *Federation Execution and Evaluation Document.* This document shall provide details for FEDEP step 6. The document results in the execution and analysis of the NIREUS Federation. The document also details hardware, network and software requirements (e.g. machines, OS and tool versions, etc). It also describes the scenario in full detail, and the initialization data files required for running different scenarios.

The steps of the FEDEP are not strictly sequential, but are better approximated as a spiraled development process. For instance, limits on federate development in FEDEP step 4 may induce changes in the federation functional allocation, and perhaps in turn help refine the federation requirements.

In FEDEP step 1, the SESG and NIREUS Rainbow Team have defined the set of objectives and developed a common understanding of resources and restraints [2]. In step 2, the NIREUS Team developed a conceptual model that sufficiently describes the real-world operational mission in the NIREUS problem space. Specific federation requirements are documented here. In step 3, the NIREUS colored teams allocate required functionality to federates, while focusing on Federate and Federation re-use. At the time of writing this paper, NIREUS is involved in Step 4 of the FEDEP process. The NIREUS colored teams negotiate the Federation Object Model (FOM) and agree to other "treaty" elements such as coordinate systems, common databases, consistent data formats, etc. The federate software development has started for both the federates and the Test Harness. When the first versions of the federates will be finalized, each federate is first tested within the context of the Test Harness, and integrated on the NIREUS integration site (Step 5). A concurrent activity is the development of the scenario, the presentation and demonstration outline. In the fall of 2001, the NIREUS federation is executed, outputs are generated, and results provided to the SESG (Step 6).

5. Conceptual Modeling

The NIREUS goal for the scenario development activity is to describe the steps of Vertical Take-Off and Landing (VTOL) operations with sufficient detail to allow the NIREUS participants:

- to evolve the scenario into one that fully meets their goals and objectives, and
- to help guide the execution of the simulation event.

This complete scenario describes all phases of the VTOL operations from VTOL operation preparation (e.g. vehicle check list proceeding, warm-up procedures) through operations (take-off, mission and landing) until vehicle storage and maintenance [3].

After the complete, detailed scenario had been developed, a subset of this scenario was chosen to be used for the demonstration in 2001. This demonstration is focussed on the final approach and landing of the air vehicle. The other aspect of the complete scenario is left for future development.

The NIREUS conceptual information flow was originally developed by the ST-SBDVP members in 1999 [2]. It provides a high level conceptual model for the military operation described in the scenario. This conceptual model reflects the three modeling areas within our federation: ship modeling (blue), air vehicle modeling (yellow), and landing system modeling (green).

The conceptual model has been further discussed and refined during NIREUS working sessions, including considerations of what calculations should be conducted at runtime in the federation for the demonstration because they are too computationally intensive. The conceptual model was used heavily to facilitate the discussions by the multi-national working groups during 2000. Expression of the problem space in conceptual terms has been particularly effective because the team members from the blue, green and yellow teams are drawn from experienced modelers, but people inexperienced with distributed simulation and HLA. The conceptual model has been a valuable tool in the development of the simulation requirements by the individual teams, and has acted as the central "rainbow" agreement from which the functional allocation and federation design have ensued.

The blue, green, yellow and red teams used the general federation requirements [2] and the conceptual model to specify the functional requirements for their parts of the federation [3]. The input and output requirements of the functions of each team with the functions of the other teams are specified using context diagrams and detailed tables. These tables are used for development of the FOM, see section 6.

6. Federation Development

The 'functional allocation' and 'selection of federates' based on the functional requirements was discussed within the complete NIREUS Team, and was driven by the availability and capabilities of existing *models* within the participating nations. Obtaining the necessary information about existing models for the purpose of re-use in the NIREUS Federation has been a lengthy process.

The general approach in NIREUS is that the model developers (non-HLA experts) provide their models to the HLA simulation developers (non-model experts) who actually write the HLA wrappers. This approach requires a lot of communication between the teams and between the members of the individual teams to build a consistent federation. In order to construct the NIREUS FOM, a NIREUS Federation Data Flow Diagram was used to identify the requirements for the interfaces between the federates. This data flow diagram was also very useful in the communication between the model developers and the simulation developers.

The NIREUS FOM is based on the Real-time Platform Reference (RPR) FOM v 2.0 [5]. This FOM is used as a starting point for the FOM development. Compatibility with this FOM permits the use of COTS visualization tools for real-time distributed simulation.

A special NIREUS team meeting was devoted to the construction of the draft FOM, in which both model developers and simulation developers participated; before this meeting, most participants followed the 'HLA/RTI almost hands-on training course' by DMSO/Aegis. During this meeting, each colored team discussed and evaluated the proposals of the red team (responsible for integration). The red team added NIREUS specific additions to the RPR FOM based on the input and output requirements of the colored teams. The principal objects and interactions were identified and the RPR-FOM was modified to reflect the decisions. Further proposals for modifying the NIREUS FOM have been discussed extensively with all teams to cover all requirements and leave no room for misunderstandings about what is communicated by the federates through the RTI.

The existing simulation models, that are eligible for re-use, were not documented in a Simulation Object Model (SOM) format. During the FOM negotiations, the experts' knowledge about the models was converted into FOM agreements by the red team. Currently, the details are still being discussed, regarding the usage of (local) coordinate systems, and the proposed attributes and parameters, in terms of definitions and data-types. The FOM construction is a process that will be completed after multiple iterative discussions between the different experts.

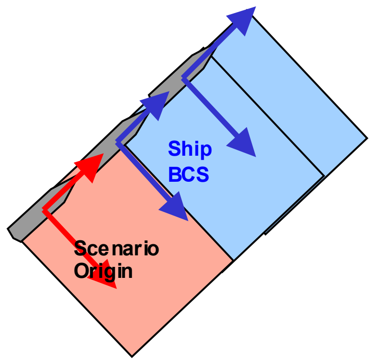

Figure 3 Local Reference Systems: the Scenario Coordinate System is aligned with the Ship at Simulation Time zero; the Ship Body Coordinate System moves along with the Ship.

Within most individual federates positions and orientations are defined in a local coordinate system defined by the origin of the scenario. Using this scenario coordinate system in the FOM to express the true positions and orientations of ship and air vehicle simplifies the task for most federate developers (see Figure 3).

The definition of reference points on the ship and air vehicle took a long time before agreement was reached (and still there is some doubt whether all implications are known for re-use in the legacy models). Eventually, it was decided to have the federate developer choose an arbitrary reference point and express the other positions of interest (see Figure 4) in terms of this reference point (and the local body coordinate system).

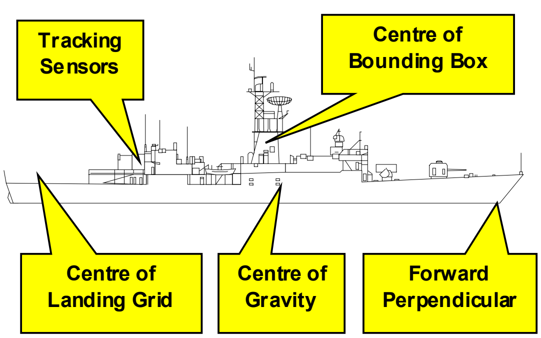

Figure 4 Possible Ship Reference Points

Before state vectors are communicated via the RTI, a conversion to the geocentric coordinate system (Earth Centered Earth Fixed) is performed, as defined in the FOM and known from the DIS standard, now instantiated with the WGS-84 reference earth ellipsoid. This solution allows easier re-use of the NIREUS Federates in other federations and enables the use of existing COTS tools (e.g., visualization federates) in the NIREUS Federation. To help the federate developers with these mathematical conversions, the red team supplied the developers with conversion routines to convert between the scenario coordinate system and the world coordinate system.

Another challenging subject, for all (distributed) simulations, is the subject of initialization (data). The requirements regarding the initialization data are quite flexible until all models and their data needs are known and the scenario is described in detail and tested. Until now, a long list of initialization data is identified, ranging from scenario positions to the characteristics of the ship and air vehicle, the sea state parameters, and so forth.

The initialization data is to be provided by the 'Federation & Scenario Management Federate'' (see Section 3). The choice for this federate was an existing (Australian) federate, called Virtual Ship Execution Manager (VSEM), described in [4,6]. This federate has the following (incomplete list of) properties:

- Synchronization of start-up and shutdown activities. VSEM uses four HLA Synchronization Points associated with the VSEM State Transition Diagram for an HLA federation execution [4].
- Enabling the federation to run multiple simulation runs within a federation execution (useful for Monte Carlo Simulations). VSEM uses the save and restore RTI services if more than one iteration is requested. This allows the federation to 'reset' the logical HLA time to zero at the beginning of each next iteration.
- Enabling the federation to dynamically create simulation HLA objects and assigning the created objects to a kind of hierarchical structure. This is done through specific HLA Interactions which also contain initial attribute values.
- Initialization data that is not represented explicitly in the FOM, such as local federate parameters, can be specified in an XML script for which VSEM will send HLA Interactions.
- VSEM uses conservative time management to support simulation determinism and the tool implements an HLA Interaction to send a specific random seed value.

Most VSEM properties are exploited in the NIREUS federation, except for the use of multiple simulation runs and the use of hierarchical object relations. More information about VSEM is described in [4,6].

The preliminary last step in the development of the FOM was the adaptation of the FOM to be able to use VSEM, with respect to initialization data and the use of synchronization points. The SOM of VSEM was merged into the NIREUS FOM.

The class table of the resulting NIREUS FOM is shown in Figure 5. The table shows the three application specific additions to the RPR-FOM. The new object classes are all derived from RPR-FOM object classes: 'UnmannedAirVehicle' from Aircraft, 'Ship' from SurfaceVessel, and 'LandingAlgorithm' from EmbeddedSystem. The object classes Manager.Federate and Manager.Federation are used for execution management (MOM services). A consequence of this particular FOM for NIREUS is that multiple federates will subscribe/publish different attributes of the same object, so the NIREUS federation will gain experience with the HLA Ownership Management services.

Because the Virtual Ship Execution Manager (VSEM) was chosen as scenario/execution manager, all federates must subject themselves to the controls of the VSEM State Transition Diagram [6]. The federates must be able to handle the announcements of synchronization points, and they must subscribe to the execution management interactions of VSEM.

Apart from the FOM and the coordinate system issues, the use of different HLA Time Management services is considered within NIREUS. The federates should support conservative time management services; all federates are time constrained and may be time regulating. For the demonstration, NIREUS aims at a (near) real-time simulation, and it is investigated what the different time-steps of the models should be within the VV&A limits (although the 2001 interim demonstration does not have strict validation requirements).

To support the integration process, the need arose for a NIREUS Repository to exchange data and working documents. Initially, an E-mail reflector was considered to distribute data, but this imposed some legal problems, as the owner of the reflector is legally responsible for distributing (classified) information that may be provided (unintentionally) by other partners. Eventually, an FTP-site was chosen as a good and cost-effective alternative. In our opinion, this works even better than an E-mail reflector. Developers are informed by E-mail about the existence of updates of documents and available simulation assets, such as the latest FOM, VSEM scripts, co-ordinate conversion software, etc. When these changes are of interest to a particular developer at a certain time, the repository can be accessed at all times when it is actually needed.

NIREUS_FOM_v0.7 - Object Class Structure Table

Class1	Class2	Class3	Class4	Class5
BaseEntity [26] (PS)	PhysicalEntity (PS)	Platform (PS)	Aircraft (PS)	UnmannedAirVehicle (PS)
			SurfaceVessel (PS)	Ship (PS)
EmbeddedSystem (PS)	LandingAlgorithm (PS)			
Manager (N)	**Federation (N)**			
	Federate (N)			

Figure 5 FOM Object Class Table

7. Federation Integration

Integration planning is guided by a demonstration to NATO in the fall of 2001. The red team is responsible for the integration planning and technical integration support. A separate team is formed to prepare the presentation and demonstration. To support the tasks in FEDEP step 5, federation integration and testing, a Test Harness is provided to the NIREUS Federation developers.

7.1 Test Harness

The NIREUS Test Harness serves several purposes:

- The NIREUS federates are developed in parallel in different participating nations. The Test Harness provides a tool for testing their federate at their local development site before all other federates are available. The federate developers want to test interoperability via the RTI (i.e. FOM data exchange and HLA services) and the interoperability of the federate with the VSEM execution manager.
- The Test Harness is used by the red team to test execution management (e.g. scenario initialization, use of synchronization points, visualization, data logging, data marshalling, performance) to assist in federation development.
- During integration, the NIREUS federation is build in an incremental way. One by one, the test federates will be replaced by the 'real' ones. If the federation does not work after replacing another federate, the Test Harness may provide an excellent tool in finding which federate is responsible for the failure.

To be able to implement those purposes the Test Harness complies with the following requirements:

- The test harness is an HLA federation that contains the same federates as used in the NIREUS demonstration federation (except for the air wake federate, and the visualization federate (due to license restrictions)). The test harness contains the scenario manager (VSEM) that will be used in the demonstration federation, which greatly improves the potential capabilities and value of the Test Harness.
- The Test Harness supports the NIREUS FOM. Each federate has the same SOM as its representative in the demonstration federation. So it subscribes/publishes the same object classes and attributes and interactions, and it registers the same instances of objects.
- The Test Federates have very limited physical behavior (or no physical behavior at all). The complex computations in the real federates are replaced by simple computations. For example, path planning for the Air Vehicle is done using a simple mathematically interpolated flight path. Interactions are not guided by computed events, but generated on keyboard events.
- Each Test Federate (which is not COTS software) shall log its data communications with the RTI to file, showing HLA interactions and HLA object updates it generates and receives.
- The federate developer obtains the Test Harness in source code. This allows the developer to modify the test federates slightly in order to be able to test specific topics on the development site.
- The test harness contains the scenario manager (VSEM) that will be used in the demonstration federation.

The red team tests the Test Harness for all federation data flows, whether the FOM seems correct, consistent, and complete, and whether data marshalling is implemented correctly. Afterwards, the Test Harness is distributed to the NIREUS partners. The federate developers use the test harness to test their federate by substituting their federate for the corresponding test federate. They can run the test harness and their federate and test whether object updates and interactions are managed well. Before bringing the federate to the federation integration site, in Toulon (France), the federate must operate properly with the test harness (using face validation).

The Test Harness is not a verification tool of the conceptual model of our NIREUS federation. It only tests the correctness of the HLA communications. It has only limited support for the actual scenario. Test federates do not by default support automatic reaction on events; they notice the events.

7.2 Integration

The red team will assist the federate developers in writing the HLA wrappers for their federates, with respect to the implementation of the FOM and other HLA implementation aspects.

The integration of the NIREUS federation will take place at the site of one of the project partners (Toulon, France). This Integration Site will be equipped with several workstations in a LAN network. At this moment, an optional WAN connection has been discussed but will probably not be implemented. The site is equipped with a number of state-of-the-art PC based platforms, running a Windows 2000 operating system and the RTI (RTI 1.3NGv3.2). One system will be dedicated to running the Data Logger and the Visualization Tool.

An integration plan concerning both technical and organizational issues is drafted. The order in which the federates will be integrated is stated. The plan accounts for the fact that some federates may require other federates to be present before they can be fully integrated, e.g. the Ship Motion Prediction Federate will be integrated after the Ship Motion Federate is present. The technical documentation should be extended with the HLA/RTI services being used, and details concerning the technical infrastructure (network, etc).

Furthermore, during integration, performance results will be collected and the demonstration scenario is tested. The results will be stored in the NIREUS Repository; the Integration Site must contain an FTP connection with the internet to retrieve and update simulation assets during integration. Also the results of each integration iteration will be recorded to be able to backtrack problems found when integrating a new federate in the NIREUS federation at hand.

When problems are encountered during the integration of a federate, it should become clear if this is the problem of an untested feature of an already integrate federate, or if this problem is due to the new federate. The federate developer should be able to correct the software on the integration site; a development environment should be present. In order to cope with problems caused by dependencies between two or more integrated federates, the federate developers of already integrated federates should be present or stand-by.

The biggest integration challenge will be to have the right experts at the integration site at the right time, to solve unexpected problems, and especially during the summer holidays in Europe. Concurrently, a lot of time will have to be spent on running various scenarios, evaluating the recorded results, and preparing the final demonstration and preparation.

8. Concluding remarks

The development of the HLA NIREUS federation is not yet completed, but we have already gained valuable insights in the challenges and problems encountered in this kind of multi-national federation development, both on the technical level and on the organizational level.

The FEDEP process is regarded very effective in combining the different development phases with the various simulation development efforts. Many NIREUS team members have already gained much experience with this process and HLA.

Currently, much effort is put in the development of the individual federates and the NIREUS Test Harness by the participating nations. Many technical and practical details are yet to be resolved, but the teams progress steadily.

NIREUS Federation integration efforts will start in April 2001 when the Test Harness and the Ship Motion Federate will be integrated at the Integration Site. It will also be interesting to learn the actual value of the Test Harness and whether it will speedup the integration of the NIREUS Federation.

After having coped with the many challenges that will emerge during integration, we look forward to seeing the federation come to life in the summer of 2001, in order to prepare the 2001 NIREUS interim demonstration in the fall of 2001.

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