JAXA-ESTEC Joint Experiment of HTV-ISS Distributed Interactive Simulation

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Abstract

The ultimate purpose of the exercise was to conduct "Distributed Interactive Simulation (DIS)" of rendezvous-and-docking maneuvers by inter-connecting several dynamics simulators; representing the current International Space Station (ISS) and JAXA’s H-II Transfer Vehicle (HTV), which were developed separately of each other by ESA\textsuperscript{1}/ESTEC\textsuperscript{2} and JAXA. This paper presents the Distributed Interactive Simulation (DIS) as an essential technology that could significantly influence the way simulation system is developed and applied towards space projects. Beside the network connectivity, the feasibility of "middle-ware" technology was also assessed. These cross-continental exercises have resulted in the applications of simulation standard (HLA\textsuperscript{3}: IEEE1516 High Level Architecture) to the domain of on going HTV operational procedure development and training.

*1 ESA: European Space Agency
*2 ESTEC: European Space Research & Technology Center
*3 High Level Architecture (IEEE 1516 Standard)

1. Research Background

This work is part of the next phase of the continuous JAXA’s activities in distributed simulation technology since 1999. This paper presents the results of distributed simulation experiments relevant to the mission design of an approaching vehicle HTV (Fig. 1) which docks with the ISS via proximity maneuver.

![Fig. 1: H-II Transfer Vehicle (HTV)](image)

Fig. 2 illustrates the reference trajectory of HTV spacecraft approaching the ISS by GPS relative navigation. The vehicle finally maneuvers along the local vertical line (i.e., R-bar maneuver), and holds its position 10m below the ISS to be grapple by the US remote manipulator system. [1]

![Fig. 2: Proximity Operation Scheme](image)
This concept of collaborative work between the international agencies was initiated following the extensive discussion during "ESA/JAXA Joint Task Force", and the distributed cross-continental space simulation system has been implemented between the ESTEC (Noordwijk, The Netherlands) and JAXA (Tsukuba Space Center, Japan).

The use of geographically distributed simulation has several advantages as compared with a centralized approach in terms of cost savings (e.g., no duplication of components, re-use of already implemented hardware and software, reduction of expert travels, and long co-location of teams). Distributed simulations may decrease the development time by enabling early simulators with the associated potential for early detection of integration and operational problems. Specifically in the field of space engineering, the DIS technology offers potential applications in [2]:

1) Rendezvous & docking sequence validation
2) Operational procedure development & validation
3) Crew & ground operation training
4) Engineering evaluation and integrated testing

Simulation schemes are presented along with its implementation process, while these results may offer potential application to support other space projects and scenarios.

2. Essential Technology

Distributed Interactive Simulation (DIS) or geographically distributed simulation allows distant simulators to work together, interacting in real-time, to possibly provide predictions as in the case of a single, integrated simulator. Before this approach can be applied to space projects, it has to be established whether the current simulation and communications technology can effectively support the concrete requirements of space scenarios. The co-operation between JAXA and ESTEC has led to the application of this technology in a space context, based on well accepted standards. [3,4]

Technically speaking, the High Level Architecture (HLA) "IEEE 1516 standard for DIS protocol" has been selected as a solution for common interface protocol, and commercial ISDN lines were provided to link remote simulation facilities. The technical issues in implementing the distributed simulation paradigm are related to interoperability and to the communications links.

2.1 HLA/RTI and Interoperability for DIS

Interoperability requires the simulator to respect and to follow certain architecture in order to be able to communicate with the other or remote simulation environment. During a distributed simulation, the distributed elements "federates" i.e. HTV and ISS shall interact in accordance with the HLA interface specification. While HLA is architecture the Run Time Infrastructure (RTI) is the software which acts as an interface middleware for distributed objects to communicate interactively and to function as united software. RTI is capable of supporting operations of task execution which provides a set of functionality i.e. Ownership, Time, Data Distribution, etc. each one dedicated to a particular aspect of management of the distributed simulation (Fig. 3).

![General Schematics of HLA/RTI](https://via.placeholder.com/150)

Fig. 3: General Schematics of HLA/RTI

While the HLA is being accepted as an existing standard, its documented processes and available tools [5] (Fig. 4) made the task of linking simulations for interoperability between JAXA and ESTEC far easier, efficient, and reliable.

<table>
<thead>
<tr>
<th>Object Class Structure Table</th>
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<tbody>
<tr>
<td>Customer (PS)</td>
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<td>Bill (PS)</td>
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<td>Order (PS)</td>
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<td>Cashier (PS)</td>
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<td>Appetizer (S)</td>
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<td>Soup (S)</td>
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<td>Soup (PS)</td>
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<td>Pasta (PS)</td>
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(S) = Subscribe (PS) = Publish and Subscribe

Fig. 4: General Sample from Interface Definition & Development Tool [5]
2.2 Coping with Communication Issues [2]

Communication links, on the other hand, poses main difficulty in coping with the latency, i.e. the time that data requires to travel from the originating simulator to the receiving one. For this exercise, the benchmark “Ping” measurements provided an average value of 480ms (round-trip). Therefore, inclusion of state-prediction scheme was inevitable to assume the current value of the remote model parameters basis on the old values (dead reckoning interpolation algorithms. Fig. 5). In order to evaluate and endorse the accuracy of the dead-reckoning scheme, the results obtained from the distributed system were compared with those obtained from the non-distributed system (comparison between a real and a predicted model).

The time management function of each federates; incorporated in the RTI, makes requests to the RTI server at every instances of time update. The RTI server monitors all federates that require time synchronization, and then makes latest judgments of time update authorization. This degrades the simulation speed for those environments with a lengthy communication delay. Therefore, in order to decrease the necessary communication volume, a unique management federate called “Federation Manager” was employed in stead of the RTI’s original time management function. Using this scheme, computer’s time are all pre-synchronized to each other using modified Network Time Protocol (NTP), and each federates continue their simulation based on the computers to which they are installed. At the same time, the starting, posing, and termination orders of a simulation are transmitted to each federates by the federation manager.

3. Preparation towards HTV-ISS DIS Exercise
3.1 Benchmark with a Existing HTV Simulator

Prior to the final adaptation of the distributed computing middleware “HLA/RTI”, the functions and performance were benchmarked with a use of JAXA’s HTV “simple” simulator (Fig. 6) and several existing RTI (DMSO(R) RTI, eRTI(R)) for characteristics comparison [6,7]. This original HTV simulation environment is based on object-oriented design, and the system consists of software models of the hardware components, numerical solvers such as for dynamics and thermal conditions, the simulation framework to control the modules, and a simulation environment including DB and GUIs. Moreover, the simulator is capable of verifying on-board models (i.e. on-board software, hardware in-the-loop system) [8].

Following the above HLA/RTI evaluation, the JAXA-developed HTV simulator was again utilized to investigate the feasibility of external networks (internet/ISDN) prior to an actual cross continental DIS in which the connection between ESTEC and
JAXA Lab was provided via commercial ISDN (64kbps x2) dialup routers. With appropriate internet configuration and ISDN router setup (Fig. 7), the existing JAXA-HTV software was successfully executed while the characteristics of the network connectivity were collected by generic and open-source bench-marking software.

As for the RTI selection, DMSO® RTI (RTI-NG 1.3v6) was chosen for its immediate availability and prolonged reliability. Moreover, DMSO’s built-in feature of the “multicast” characteristics has leaded our exercise to utilize “IP Tunneling” between LANs and federates.

### 3.2 Modification for the Final DIS Configuration

In order to ensure the connectivity between the independently developed simulators (ESTEC-ISS and JAXA-HTV), the exchange of interface information (interoperability) was based solely on the documented HLA specifications (Fig. 4 for sample), and the simulators were modified separately while the engineering contents of each software was “kept black-boxed” to each other which demonstrated the notable “contents concealing” feature of RTI middleware (Fig. 8).

As mentioned in the section 2.2, the key feature of modification on the JAXA side was the adaptation of effective schemes to cope with the time delay and to maintain appropriate execution speed which was known to degrade during long distance connections i.e. applying a “Dead- Reckoning” scheme to reduce data trafficking. With appropriate software modifications (HTV/ISS control center) and DMSO RTI implementation, both the ESTEC-ISS and JAXA-HTV simulators functioned flawlessly, while the graphical features were also implemented for the simulators.

4. Test Scenario and the Final DIS Experiment

#### 4.1 DIS Test Scenario

Finally, a cross continental DIS was conducted between ESTEC and JAXA on July 2, 2003 under the supervision of section heads and related engineers. The exercise scenario was to have the simulated HTV (running on a JAXA located computer) approach to the ISS vicinity, ready to be berth to the simulated ISS (running on an ESTEC located computer). As mentioned, the data between the two simulations was interchanged in real-time using standard ISDN lines, while both sides could follow the simulation with the aid of a 3-D graphics front-end and did not require the audience to be a simulation or sub-system specialist to understand the progress (Fig. 9).

The test scenario was prepared and demonstrated with human operators in the loop playing part of HTV control+monitor, ISS mission control, ISS crew, and Federation manager. As illustrated in the Fig. 9, the spacecraft (HTV) initiated its final approach from 500m below the ISS, and continued along the z-axis until 100m relative distance where HTV makes 180deg yaw.
maneuver; for unexpected evacuation away from ISS, and holds its position. HTV controller then gives an authorization for further approach until HTV reaches 30m below ISS for the final parking. HTV controller re-issues a command to continue the final approach towards the relative distance of 10m (Birthing Point: BP) [1]. For the exercise purpose only, an emergency “abort” command was also issued before the BP to demonstrate the functional capability and to illustrate a contingency scenario applied to an operator training.

Fig. 9: R-bar Proximity Approach Scenario

4.2 Final DIS Experiment

Distributed tests and final demonstration were supported by simultaneous videoconference via dedicated ISDN link, and live 3D graphics on both sites. Two different image generation systems were linked to ISS federate on ESA side and Monitor federate on JAXA side and rendered identical scenes on both sites (Fig. 10&11). Due to long duration (more than 1 hour) of originally used scenario, scaled time factor (execution faster than real time) was used to reduce test and demonstration time.

All the prepared commands for this demonstration were successfully executed through the “graphical control panel”, and the operators had followed the scenario as planned. The engineers on both sides confirmed the capability of fully functional simulator as well as the stable performance of interactive network infrastructures. The final exercise has demonstrated an outstanding capability of utilizing the HLA/RTI protocol as well as an efficiency of applying the dead-reckoning scheme to cope with the geological latency.

Fig. 10: ISS Control Command Panel (GUI Behind) & ESTEC-side Monitor Graphics (Open GL(R))

Fig. 11: HTV Control Command Panel (GUI) & JAXA-side Monitor Graphics (JAVA(R))

4.3 Engineering Assessments during Integration

The DIS system has performed flawlessly during the demonstration; however, the following issues were brought to our attention during the integration period:
1) System-specific (incompatible libraries, access rights, etc.);
2) Network-specific (errors in network setup)
3) Interface-specific (different interpretation of shared model, coordinate, and simulation control)

For example, slightly different definitions of coordinate systems used by JAXA and HTV-DIS initially caused some interoperability problems.
5. Conclusion

The DIS exercise has proven the effectiveness of using HLA to link and integrate already existing simulations and simulators. And the work done for this exercise was an outstanding example of how interoperability could be achieved within a relatively short period of time. ESA/ESTEC and JAXA simulations and models were only interfacing each other through a pre-defined and well documented procedure based on the HTL/RTI standards. Neither side of the engineers required to share internal details of one party’s software to another party, which allowed for minimum in-person meetings and interactions between the ESA and JAXA teams during the integration. In fact, the actual implementation, integration and testing of federates were completed within less than 4 months total.

On the other hand, the engineers have to be aware of some limitations and issues during integration such as the termination of support for the DMSO’s RTI which leads to an inevitable use of commercial HLA/RTI or other standards available. Implementation of Dead Reckoning and time management algorithms may require major modifications on existing simulators for some.

The results of the demo were well received by both ESA and JAXA personnel, and the successful experiments to deploy an HLA-compliant federates between ESA/ESTEC and JAXA testify to good prospects regarding use of HLA to link simulation and training facilities of the ISS international partners. Further plans are being discussed for the next step in linking the simulators between multiple agencies.

6. Acknowledgments

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References


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