OPERA: OPERATORS TRAINING DISTRIBUTED REAL-TIME SIMULATIONS

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Abstract: OPERA is a European Commission funded project that aims at developing new concepts and technologies based on highly modular, reusable and reconfigurable distributed real-time simulation software, in order to bring training simulators to the mainstream chemical industry. Amongst all components of OPERA, this paper deals mainly with the Hybrid Modelling Framework, and heterogeneous simulation environments interoperability aspects.

Keywords: Operators training, distributed real-time simulation, object-oriented architecture, hybrid modelling framework, simulator interoperability

INTRODUCTION

OPERA is a European ESPRIT project[1] started in October 1997, which aims at developing new concepts and technologies based on highly modular, reusable and reconfigurable simulation software, in order to bring training simulators to the mainstream chemical industry. The project partners are: **Thomson Training & Simulation** (France), technology provider and project manager; **ProSim** (France), technology provider; **Fraunhofer-IITB** (Germany), technology provider; **ICI** (UK) and **DuPont** (UK), chemical and plastic industries end-users; **TCL** (Netherlands) and **VIA** (Belgium), consultants and end-users educational training institutes.

OPERA represents a new philosophy in terms of modular and configurable use of process models and other resources as well as developing the technology to achieve a massive reduction in costs while at the same time increasing the power and flexibility of these simulators. The rapid advances in computer hardware technology enable real-time applications for use as a modular operators training simulator. The linking of truly object-oriented process and control system simulation tools allows model components to be developed and used in an incremental, structured and reusable manner. Process models can be planned and developed for the lifetime of the project from design to operation.

To prove OPERA's concepts, trial its philosophy and validate its technology, three quite different prototypes are being developed for an ammonium sulphate pilot-plant of TCL, a polyester film production of DuPont, and an ICI Acrylics intermediate chemical ACH (Acetocyanohydrin) process with a Yokogawa DCS operator system.

THE OPERA ARCHITECTURE

The basic architectural approach of OPERA is to enable the reuse of existing possibly heterogeneous simulation frameworks and couple them over a real-time simulation platform. This platform is called HPCS/RT - **H**igh-**P**erformance **C**omputing Platform for **S**imulation Applications in **R**eal-**T**ime [5], and is one of the main component of OPERA.

At the core of the architecture, the simulation engines themselves are embedded in a second OPERA main component, called HMF - **H**ybrid **M**odelling **F**ramework, which relies on HPCS/RT as a common backbone. This framework encompasses all proprietary simulation environments used for continuous and discrete-event process simulation.

The physical architecture deployment of OPERA appears on figure 1. The very top level, which does not appear in the figure, is represented by end-users hardware workstations (Engineer, Instructor and Operators stations) which runs man-machine interface tools showing Java - based animations of the operators diagram. The first-level object bus, the top layer in the figure, has moderate real-time requirements (~200ms). It uses a raw CORBA implementation with few design constraints. The second-level

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[1] ESPRIT Project n°24950 of the 4th Framework Workprogramme funded by the EC.

object bus is HPCS/RT which has more stringent real-time requirements (~10ms). The Master Server manages sessions and requests between clients and HPCS/RT, while Auxiliary Servers host HMF simulation engines.

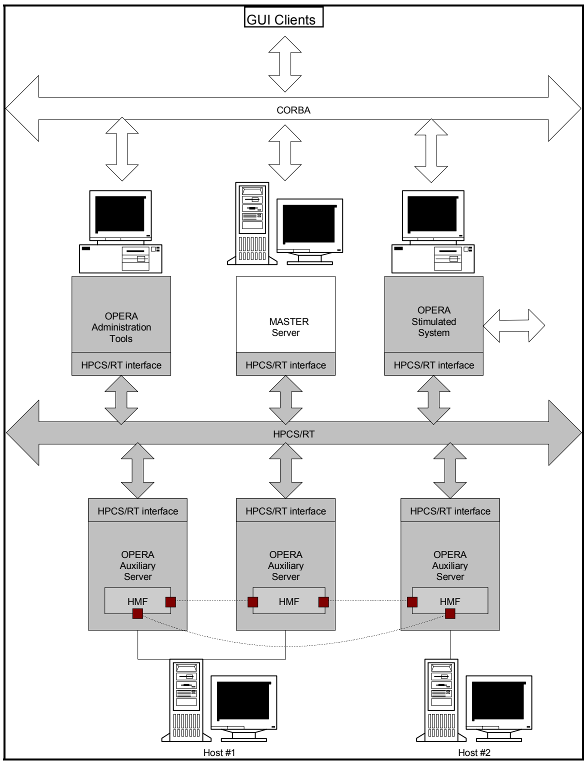

Figure 1 - OPERA simulator physical deployment

1 Distributed real-time simulation

A real-time simulation can be seen as the execution of interconnected simulation components within one logical time space. Usually this execution is done by one scheduler which is responsible for the co-ordinated time advancement. A distributed simulation is basically the same with the difference that the execution is performed by several distributed execution hosts. The challenge comes with parallelisation, when two events can be executed at the same point in universal time. Within OPERA, time management is a key point (trainee's time perception, synchronisation, clock management, real-time requirement). To satisfy these requirements, OPERA simulation components just work on the basis of a logical time concept. The logical time is a non-linear function of the scaled wall clock time, as defined in the HLA[2] [3][5].

HPCS/RT follows a master/slave approach. A Central Conductor (CC) is the global synchronisation authority for time-stepped and event-driven simulations. Local Conductors (LC) request the time advancement of their logical time at the CC and the CC grants the time advancement. The grant means that the LC can launch its simulation work independently until its logical time reaches the granted time point. After reaching

[2] US Department of Defense High Level Architecture.

this point in time, the next global synchronisation then occurs. If the simulation should be stopped, paused[3], frozen or synchronised with the real time, this has to be done only in the Central Conductor.

THE HYBRID MODELLING FRAMEWORK

As required by operators training simulation, OPERA simulators feature dynamic models that represent the transient behaviour of the simulated process, with a large validity range in order to realistically render malfunctions. They also feature a full modelling of the control system, including stimulated equipment interfaces[4] (DCS). This is the responsibility of the core Hybrid Modelling Framework (HMF) of OPERA. Amongst other subsidiary tasks, the HMF manages the continuous dynamic simulation of chemical devices, provides thermodynamic calculation services, and provides the discrete-event simulation layer for control aspects.

The HMF has been designed as a component-based framework, fully object-oriented, even at the level of thermodynamic properties calculations, to fulfil important OPERA requirements on openness and configuration flexibility. It also strongly relies on existing building blocks provided by each project partner:

- *Thalie / FluidNet* (hydraulic networks simulation), from Thomson Training & Simulation;
- *OOST* (object-oriented discrete-event simulation tool) from IITB;
- *Odysseo* (chemical processes object-oriented dynamic simulation) and *Atom* (applied thermodynamic object-oriented model) from ProSim.

1 Hydraulic network and chemical unit operations

The continuous modelling is based on a rigorous first-principle approach involving transitory material, energy and momentum balances coupled to thermodynamics properties and equilibrium equations, and finally chemical reactions models. The resulting model typically forms a set of Differential-Algebraic Equations (DAE). However, the solving is distributed between the plant-level hydraulic network and the chemical unit operation devices.

HMF interfaces directly with the FluidNet subsystem, which manages the modelling and simulation of networks of pipes, pumps, valves and all components that belong to the hydraulic domain. It offers several modelling layers of the simulated plant:

- the Technical layer (also called CAD or Topological layer), accessible through the graphical user interface, is used to define the network topology.
- the Spatial discretization layer contains finer-grained components that are automatically built from the information captured through the Technical layer. This model is then reduced using common association rules between components into *junctions* and *control volumes* objects. The process used to build this layer is called *mapping*.

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[3] Simulation is still performed, but with a zero-duration cycle time.
[4] For instance, ICI's OPERA prototype supports the Yokogawa system.

Thermo-hydraulic field differential equations (mass, energy and momentum conservation laws) resulting from the spatial discretization layer are solved globally for the whole network. For efficiency purpose, the time discretization is done directly inside the model's equations to yield a global sparse linear system solved at regular time cycle.

Chemical unit operations are modelled and simulated using the Odysseo framework which provides modelling classes structured in *Elementary/Composite Device* and *Ports* objects [6]. Complex devices such as the ones found in the various OPERA prototypes (distillation and absorption columns, reactors, crystalliser, heat exchangers, etc.) are hierarchically structured in inter-connected elementary devices such as theoretical separation stages, control volumes, heat transfer cells. They are simulated by solving a global Differential-Algebraic Equations (DAE) system using a backward-difference algorithm (Gear) [6]. Each elementary device contains a local Atom material system supporting thermodynamic calculations. A specific OPERA package provides specialised property objects as an extension of the Atom material framework [4], whose underlying principle has been retained for the *material template* concept of the CAPE-OPEN project [1]. Its flexibility is the key point in representing ionic dissociations, inert / incondensible components, etc. in an efficient way to fulfil real-time requirements, knowing that TCL's ammonium sulphate plant prototype involves complex solid-liquid-vapour systems and electrolyte solutions. This flexibility also allowed to design a property calculation cache strategy (« stamped » variables) [4] that avoids repeating time-consuming calculations. First experiments show that up to 70% of calculations can be saved in the best case (low transient states, or else stiff conditions with repeated calculations at the same point) with no impact on the properties code. By using full-featured models, this approach radically departs from the table-based thermodynamic approaches usually found in common training simulators.

2 Command & Control

The Command & Control part of the simulated plant is managed by the OOST simulation tool embedded in HMF (fig. 2). This tool is based on a general *Function Block* model relevant to modern automation systems based on fieldbus [2]. It uses network of function blocks, followed by the assignment of function blocks to resources and a scheduling model. A function block is an automaton with data / event inputs, data / event outputs, and states. The states are used to model the various modes of function blocks such as out of operation, manual and automatic. Function blocks are linked by connecting the outputs to inputs, whereby each data input is connected to exactly one data output and each event input is connected to exactly one event output. An input or output may be connected to an external instance representing the technical process / user interaction (instructor / operator stations) or the communication system. In concrete fieldbus function block specifications, the link to the

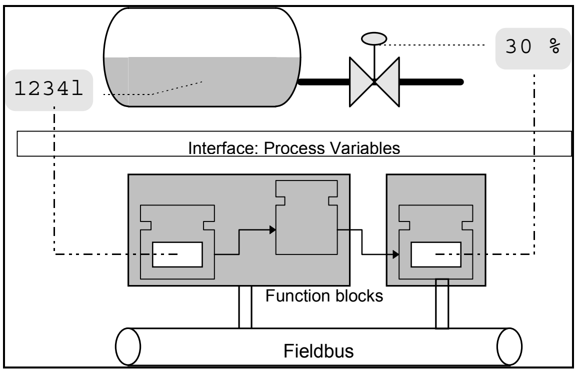

Figure 2 - Physical to IaC relationships

process is often achieved via special « transducer » ports. These ports model the A/D (analogue / digital) and D/A (digital / analogue) converters between the physical process and the controlling equipment. Typical function block definitions comprises PID controllers, switches, lags, integrators, impulse delays, etc.

3 Simulation interoperability

Recent developments in distributed simulation (HLA [3]) have evidenced the feasibility to achieve broad real-time simulations by coupling heterogeneous simulators units together. To achieve coupling of autonomous simulators, *a Proprietary Simulation Environment* (PSE) interface has been defined to abstract OPERA access in the selection of simulation components to be loaded and run at configuration-time, and to control simulation at run-time. PSE runtime interface manages simulation states (i.e. running, frozen, paused), synchronisation and monitoring, and heavily relies on the DiSOM (Distributed Simulation Object Model) components introduced by HPCS/RT [5]. This model defines the OPERA concepts of *Ports* and *Atomic/Composite Components*[5] as a common interoperability mean between distributed components. The OPERA object-oriented framework relies only on a little set of concepts that can be easily mapped upon a broad range of legacy object packages, through code encapsulation. Thus, HMF provides mappings between similar concepts from the wrapped proprietary environments, and the DiSOM model.

3 .a Continuous simulation

Continuous simulation in HMF is time-stepped, i.e. the synchronism between distributed models occurs at the end of simulation cycles[6] upon HPCS/RT local conductor requests. Hydraulics and unit operation devices form two separate simulation layers at the plant level, with different causality, that reconcile at each cycle.

During one simulation cycle, the following procedure takes place: the hydraulic network (pipes, valves and pumps) is solved globally by FluidNet to determine flows (in value and direction) between devices, considered as pressure nodes in the hydraulic network; each device is then solved concurrently, depending on the distribution configuration of the simulator, to determine the thermodynamic and physico-chemical behaviour of the plant depending on FluidNet results. This two-tier strategy allows to: easily breakdown the plant into software distributable devices; separate numerical component with different dynamics (pressure and physico-chemical dynamics), thus leading to efficient calculations; finally, interoperate FluidNet and Odysseo through very few common interface concepts.

[5] The A*tomic Component* represents the smallest unit of parallel distribution that can be mapped onto a simulated process unit.

[6] Not to be confused with solvers differential integration steps, which actually vary in size.

Any OPERA chemical device is built upon the Odysseo framework and embedded in a dedicated OPERA DiSOM-like component[7] that establishes all the necessary links with the FluidNet network (fig. 3). The embedded device is then seen by the hydraulic network as a regular « control volume » providing pressure, temperature and composition information. The embedding OPERA component uses specific *two-way ports* to interface the internal device with the hydraulic network:

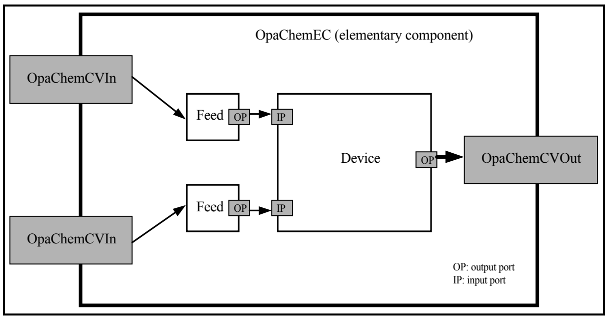

Figure 3 - Chemical device embedding

- as seen from FluidNet, those ports have no causality and represent the device itself as an hydraulic control volume (pressure node). For simple, non-composite embedded devices, these ports actually access the same Odysseo objects;
- as seen from the embedded device, ports can be either input or output ports, and represent different interfaces to the upstream or downstream devices. The device itself, while simple from the FluidNet point of view, is actually a full Odysseo flowsheet object that may be internally decomposed [6].

By extending the general DiSOM concepts at the chemical process level, these two-way ports are one of the most important result in the HMF design, and represent a strong basis for heterogeneous dynamic process simulators interoperability, as pursued by the CAPE-OPEN project.

3 .b discrete-event simulation

The command & control part is simulated as a discrete-event process. HMF introduces a mapping of the OOST model components onto the equivalent DiSOM's atomic components. OOST thus directly interfaces with HPCS/RT, and runs on its own auxiliary server. The connections and the execution rules for function blocks are defined by using the notion of control loop, which are implemented by instances of control loop model components.

The fieldbus configuration comprises the distributed execution of the fieldbus application within fieldbus devices. A generic fieldbus device and a fieldbus segment model component are used to model a fieldbus configuration. Fieldbus devices are responsible for executing the function blocks, and the fieldbus segments are responsible for communicating the function block parameters between remote function blocks [2].

The discrete-event Scheduler implements the interface from OOST to the Local Conductor (LC) and the derived DiSOM components. Any local event that requires a time advancement will be synchronised with the LC. Most of the synchronisation requests are granted by the LC by a local decision, because they are inside the look-

[7] not directly a DiSOM component, but based on it and aiming at the same functionality.

ahead boundary (LBTS). Only requests for times after the LBTS are synchronised by the CC.

CONCLUSION

As part of OPERA, HMF demonstrates the feasibility of the industrial-strength integration of heterogeneous existing chemical process simulation frameworks upon which it is built. HMF thus achieves a tight balance between important requirements:

- real-time calculations: calculations should be completed in time ;
- sufficient accuracy: calculations should provide results that are sufficiently accurate not to denature the dynamic behaviour of the simulated plant, especially in the case of malfunctions realistic simulation;
- interoperability management: partner's existing simulations framework are integrated seamlessly, based on the HPCS/RT DiSOM components. While similar to the CAPE-OPEN approach, OPERA extends it to real-time dynamic simulation.

OPERA offers a range of new technical features coupled with ongoing advances in hardware and software technologies and a cost of operators training that can be afforded by typical chemical plants. The OPERA vision aims at providing access to training simulators, to small production units (e.g. for batch, semi-continuous or fully continuous processes, small scale or bulk). OPERA simulators can be developed for speciality and complex chemicals or simpler products, from products made by synthesis to those made through extraction/separation from natural sources.

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