

A FULL-SCOPE APROS-BASED SIMULATOR FOR HUMAN-MACHINE STUDIES

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Abstract

The Institute for Energy Technology (IFE) is a Norwegian-based energy research institute operating within the nuclear and petroleum domains. IFE is the host of the OECD Halden Reactor Project (HRP), an international research project funded by more than 100 nuclear organizations in 17 countries. The overall aim of the HRP is to enhance safety and efficiency when operating nuclear power plants, through research activities such as fuels and material performance and human-machine and control room studies.

The main research tool for the activities within the human-machine area is a simulator-based experimental facility called HAMMLAB (Halden Man-Machine Laboratory). HAMMLAB is equipped with three full-scope simulators, operated through a flexible control room and experimental infrastructure. The nuclear simulators of HAMMLAB are the French Fessenheim 1 PWR and the APROS-based Swedish Forsmark 3 BWR. Forsmark 3 is one of the largest nuclear power plants in Sweden with 3300 MW thermal power and 1200 MW electrical power. HRP's Forsmark 3 simulator, HAMBO, was developed in close cooperation with VTT in Finland, and was installed in HAMMLAB in 2000. HAMBO has since then been continuously updated, and has been the main vehicle of numerous human-machine experiments and studies within the Halden Project.

Keywords: APROS, experimental simulator, human-machine studies.

Presenting Author's biography

Christer Nihlwing. Has worked fifteen years in the Swedish BWR power plant Oskarshamn 3 as an operator and shift supervisor. After that, ten years on IFE as a process expert on BWR's and responsible for the BWR simulator HAMBO.



1 Introduction

The HAMBO simulator was developed as a joint effort between IFE and VTT in Finland over a three-year period from the beginning of 1998. The simulator has been used for experimental purposes within IFE since 2002. The simulator is a full-scope simulator of the Forsmark 3 power plant in Sweden (boiling water reactor). Forsmark 3 is one of the largest nuclear power plants in Sweden.



Fig. 1 Forsmark 3

Forsmark 3 is a highly automated BWR plant with one turbine, producing 1200 MW electric power. The reactor produces 3300 MW thermal power with 700 fuel elements and 169 control rods.

The HAMBO simulator model is running in APROS 5.07 Huge and Grades 1.3, and consists of 1280 nets/diagrams, and both a 1D and 3D core. Some key figures are shown in table 1.

Table 1. Some key figures of the HAMBO model

Reactor macro assemblies (1D/3D)	1 / 169
Reactor nodes (1D/3D)	25 / 4225
5-eq. flow model nodes (1D/3D)	240 / 940
Containment nodes	5
Heat structures nodes	1840
Heat exchangers	77
Turbines / sections	1 / 15
Valves	1700
Pumps and fans	160
Analog signals	~13 000
Binary signals	~53 000
Analog signals to operator interface	2160
Binary signals to operator interface	7278
Binary signals from operator interface	2650

The HAMBO simulator is used for experimental purposes in the Halden Man Machine laboratory (HAMMLAB). Most experiments are conducted using Swedish operators. HAMMLAB has a screen based control room as shown in Fig 2. In HAMMLAB one has the possibility to select from three simulators, in addition to HAMBO, a French PWR simulator and an oil platform simulator. The HAMBO simulator and its

software infrastructure is running in the XP environment. The whole simulator with its infrastructure is running on a two-cpu laptop computer.



Fig. 2 Halden Man-Machine laboratory.

All simulators are connected to an integrated platform transferring data from the simulator to the displays and orders from operators to the simulator. The simulator is connected to the integration platform through the PROCess INterface (PROCINT) module. The PROCINT module uses the APROS communication library, ACL, for data communication with the simulator. The HAMBO simulator is running at 10 Hz and the rest of the system at 3 Hz. The architecture of the integration platform is shown in Fig. 3.

System Architecture

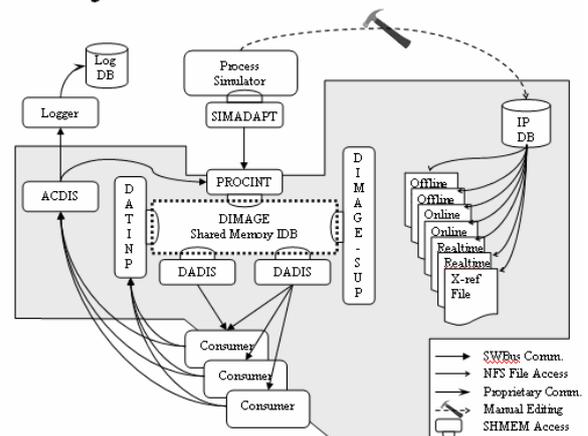


Fig. 3 Integration platform.

Other applications are connected to the integrated platform, as shown in Fig. 4, and together they constitute the full infrastructure of the HAMBO simulator.

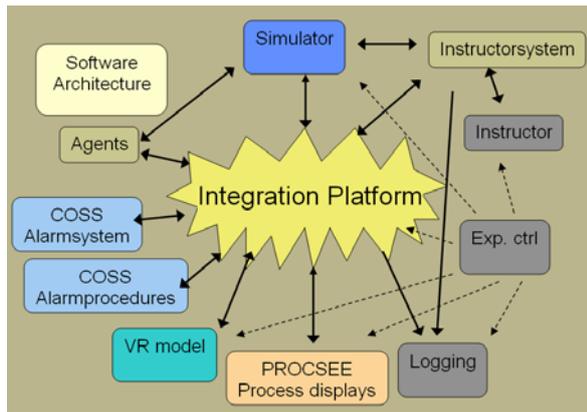


Fig. 4 Infrastructure of Hambo.

2 The HAMBO simulator

As earlier noted, the HAMBO simulator runs smoothly on a two-cpu PC. This makes it very easy demonstrate HAMBO off HAMMLAB. Generally, the model together with the infrastructure is very stable and that is important when we run complex, heavy transients for a long time during experiments.

2.1 The HAMBO model

The whole simulator model has been modeled using standard APROS components. The model is based on plant drawings, operating instructions, and training material. Plant measurements and transient data from Forsmark 3 training simulator have been available for HAMBO tuning, see example Fig 5.

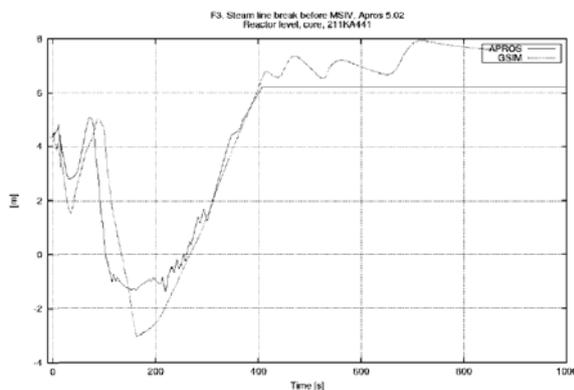


Fig. 5 Comparing water level of steam line break.

One prerequisite when specifying the extent of the model has been that every measurement and alarm and everything operable in the main control room of the reference plant must be modeled to work in a similar manner. Most of the systems and components have been modeled physically. In cases where features of APROS do not admit physical modeling, a workaround has been done in order to make e.g. measurements behave correctly.

2.1.2 Reactor core model

The simulator contains two nuclear reactor core models, the 1-D core model and the real-time 3-D core model.

The 1-D model is on the physical basis a two-energy group, six delayed neutron precursor group model. In the neutronics model, the core is divided axially into 25 sections of equal length. The thermal hydraulics and the fuel rod consisting of fuel, gap and cladding is described using the reactor process component. In thermal hydraulics the core is also divided axially into 25 nodes of equal length. Heat conductance in the fuel rod is described in the standard manner with 10 radial nodes in the fuel-rod model. Core thermal hydraulics is described with the 5-equation thermal hydraulic model of APROS.

In the model, the option of individually moving control rods is used. Thus, the movement of each of the 169 control rods can be taken into account also in the 1-D model and the rods have been connected to the automation driving the rods.

The 1-D model uses neutronics cross-section data that was condensed from the original full 700 fuel assembly 3-D core cross-section data. The cross sections describe the Middle of Cycle (MOC) core status of cycle 7 of Forsmark 3.

In the 1-D model, the user can observe the flux, power, fuel temperature, coolant density, coolant temperature, void fraction and boron concentration in each axial node, the core average values of these variables, the core axial power profile, and the position of each individual control rod.

The 1-D model is very fast and takes less than 2 % of simulator calculation capacity.

The 3-D model is a two-energy group, six delayed neutron precursor groups model. The neutron fluxes are solved according to the finite difference method.

The 3-D core model includes 169 macro fuel assemblies divided into 25 axial sections of equal length. The macro fuel assemblies are placed into 29 thermal hydraulic flow channels that are also divided into 25 axial nodes of equal height. The macro fuel assemblies are created principally by combining the four assemblies surrounding one control rod. The model describes all the 169 control rods existing in the core. Fuel rod heat conductance calculation in the 3-D model is identical with the fuel rod calculation method in the 1-D model. For each fuel assembly a separate fuel rod calculation is performed. The core thermal hydraulics is described by the 5-equation thermal hydraulic model of APROS. The 29 thermal hydraulic

flow channels were created by combining principally 6-8 macro fuel assemblies to one thermal hydraulic channel. However, one of the macro channels was replaced with 9 individual thermal hydraulic channels in order to allow the description of single control rod movements in a realistic manner. The construction of the 3-D reactor core model is presented in Fig 6.

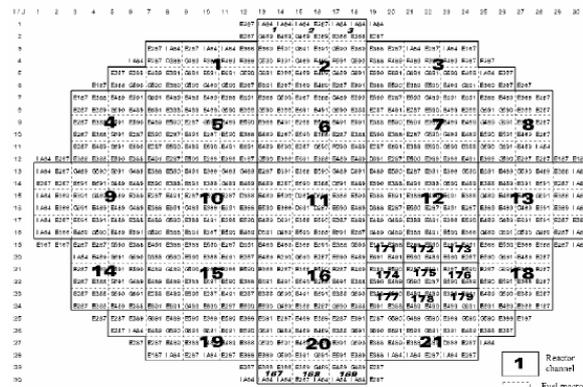


Fig. 6 Outline of the real-time 3-D core model

The 3-D model uses a condensed neutronics cross-section set that was created from the full 3-D cross section set at VTT. The cross sections describe the Middle of Cycle (MOC) core status.

The number of thermal hydraulic channels and fuel assemblies had to be optimized in order to fulfill the real-time requirement set to the simulator core model. In neutronics the most reasonable alternative is the combination of the four assemblies surrounding each control rod.

The thermal hydraulic calculation has more degrees of freedom when trying to optimize the calculation speed than the core neutronics. The channel division selected fulfils the real-time requirements and gives reasonably good spatial description in the core.

From the 3-D model the user can observe node-wise such parameters as flux values, power, and fuel temperature. From the thermal hydraulic channels the user can observe node-wise the coolant density, coolant temperature, void fraction, and boron concentration. The core average values as well as axial power profile are provided, too. The user can also observe all calculated variables from each axial level of the reactor core, as shown in Fig 7.

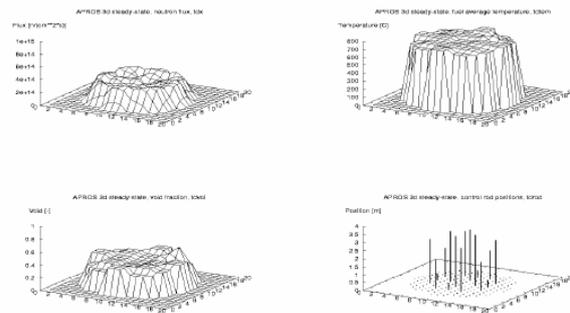


Fig. 7 Fast neutron flux, fuel temperature and void fraction distributions as well as control rod positions in the 3D-core model.

We are this year starting a work together with VTT in Finland to integrate the 3D core into the model itself. This is done because we need the possibility to simulate local criticism including not only neutronics feedback, but also thermal heating into the water in the reactor tank.

2.1.3 Reactor vessel

The reactor vessel and systems inside the vessel are modeled using 5-equation components. The 5-equation nodes and branches take into account two-phase flow with phase separation and thermal non-equilibrium. The whole vessel is modeled with 53 nodes out of which the 1-D core is described with 25 axial nodes. The separate 3-D core model can be run in parallel with the main model, but it does not affect parameters in the main circuit. The down-comer is in the lower part of the vessel formed by the annular area between the reactor vessel wall and the moderator tank. In the upper part an annular steam column is formed by the steam dryer casing. In the steam column and in the region where the water level normally is, the nodalization is a little bit denser than in the down-comer. In the lower plenum, the flow is divided into a major path going through the reactor core, and a minor (about 14%) core bypass flow path. The bypass channel simulates in the lower part the volume occupied by the control rod guide tubes and in the core region the flow between the moderator tank and the fuel assemblies and between assemblies. The upper plenum and the steam separator tubes are described by five nodes. The highest node works as a separator. The real separation mechanism includes dynamical forces, which cannot be modeled with traditional thermal-hydraulic models. Here a simplified approach is selected, where the node is fully separated, i.e. steam is leaving from the top of the node, and water is directed downwards from the bottom of the node. The separator node includes both the volumes inside and outside the separator tubes. The steam dryer section is described by one node and the steam dome also by one node.

The reactor vessel wall is described by heat structures where heat from the outer surface is transferred to the containment. Internal heat structures describe the moderator tank, the core support plate and core support grid, the fuel rod bundle walls, the steam separator tubes, the steam dryers and the dryer shroud. Pressure, level and temperature measurements are modeled with four channels even though the thermal hydraulic process is 1-D. The level measurements are based upon pressure difference measurements between certain elevations.

The 169 control rods are simulated as a part of the reactor core model. Their effect on the reactor power as function of rod position is accounted for both in the 1-D and 3-D neutronics models. The control rod drive system is not physically described, but the logic and interlock signals for allowing movements when controlled by the control rod operation system, are fully modeled. All rods are moving with a speed of 100% / 4 min, when controlled by the system. In case of a reactor trip, the rods are inserted by the hydraulic scram system with a speed of 100% / 4.2s. The division of the control rods into different scram and maneuvering groups is accounted for, as well as their connection to different electricity supplies. The control rod positions are measured by the control rod position indication system.

2.1.4 Process and control system

The process and control systems that are needed for the operator to interfere with the process in different plant states from cold shutdown to full power and in transients are modeled. IFE personnel can easily make changes to the model such as putting in new places for leakages, and make changes to the logic in order to make new malfunctions. This is a very important feature in order to adapt the simulator to different experimental conditions. If you know the process you will easily find the way in the Grades user interface, see an example in Fig 8.

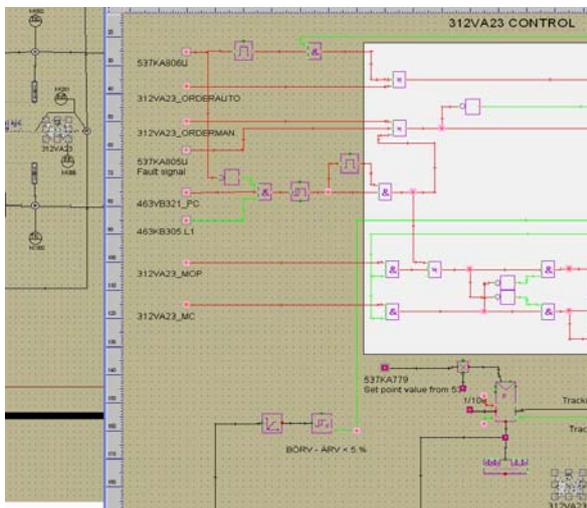


Fig. 8 View from Grades inside HAMBO.

2.2 Instructor system.

The instructor system of HAMBO, called Rhambo, is built by IFE and uses a script language that makes it possible to run complex scenarios in an identical way for different crews. This is extremely important in the type of experiments being performed at IFE. Rhambo can also run the simulator from full power to cold shutdown and back to full power again in the same way as an operator would do, and saving snapshots on the way.

Rhambo is connected directly to the simulator both through the command channel and through the synchronous data out channel, and can in that way reach every signal in the simulator. It is also connected to the integration platform to be able to interfere with the displays, change displays, painting on the displays and much more.

An example of a scenario in the script language can look like this:

```
//Scenario 04 Start from 20% power and up
//Drain switching with problem

cniwait 10
//Valve 463VA20 stuck in close position
modis 463VA20 VA12_MALFUNCTION(1) 1
cniwait 1

//Not able to open 423VB7 manually
modis 423CO3_XB57 value F
cnimancom modis 423CO3_XB57 value T
cniwait 10
//Not able to close 423VB7 manually
modis 423CO3_XB62 value F
cnimancom modis 423CO3_XB62 value T
cniwait 10
cnibreak
```

2.3 VR-model

A VR model of parts of the Forsmark 3 plant is developed at IFE and connected to the simulator. The VR model consists of 20 rooms, modeled using the CREATE tool [1]. In the model, the field operator can access local objects such as valves, pumps, breakers in switchyards, diesel engines and so on. Views from the VR model are shown in Figures 9 and 10.

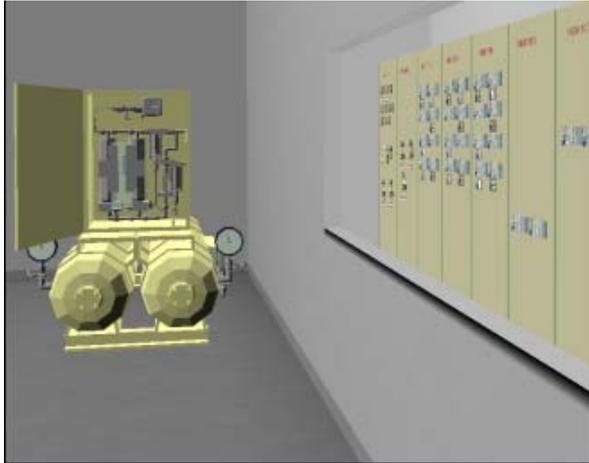


Fig. 9 VR view of start air and local control room for the diesel engine.

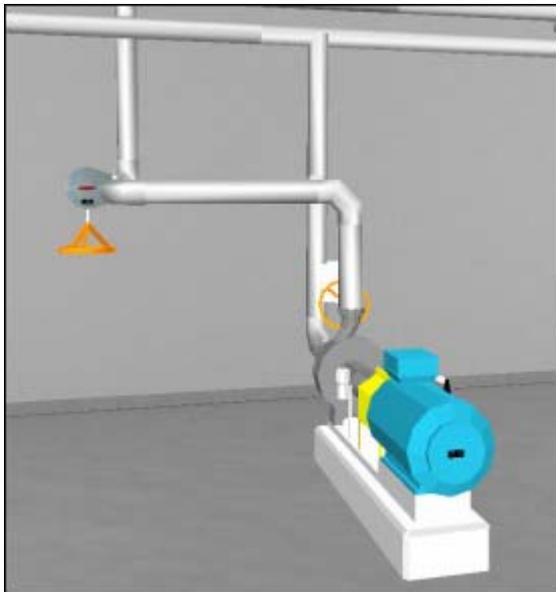


Fig. 10 VR view of process room.

2.4 Process displays

The process displays of HAMBO are developed in the tool ProcSee [2]. It makes it possible to implement new and innovative ideas for visualizing the process, see example in Fig 11.

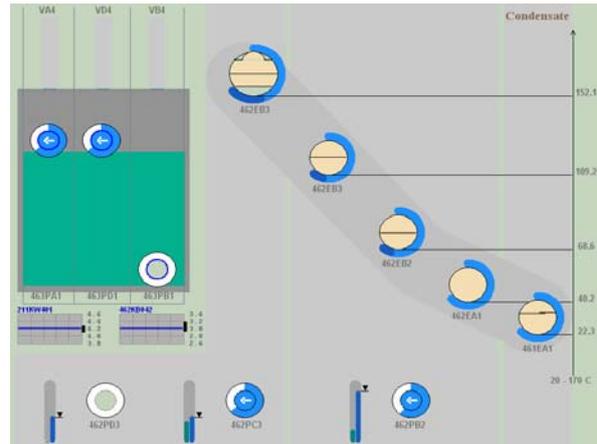


Fig. 11 Innovative process display in ProcSee.

2.5 Logging system

The logging system has the possibility for logging all process data in and out from the simulator together with all type of operator actions. If needed, one can make replays of the whole scenario to be able in detail to study the operator's behavior.

3 Selected experiments performed within the HAMBO simulator environment

This chapter gives a very brief description of a few of the experiments performed in HAMMLAB using the HAMBO simulator. References are provided for those having special interest in details.

3.1 Effects of task complexity on operators' performance [3]

This experiment was the first in a series intended to inform Human Reliability Analysis (HRA). The experiment studied eight loss of coolant accidents (LOCA) scenarios with varying complexities. The scenarios were grouped into low, medium and high complexity.

This experiment was a real challenge for the simulator. It was very heavy transients (LOCA) in the scenarios and the simulator was new but with hard work and support from VTT we made it.

3.2 Procedure Automation and effect on human performance [4]

The expected outcome of the study was to provide input for guidance on computerized procedure systems. The experiment varied the level of procedure automation and measured how this impacted operator performance.

3.3 The task complexity experiment [5]

The purpose of the experiment was to explore how additional tasks added to base case scenarios affected the operators' performance of the main tasks.

This experiment consisted also of very heavy transients but the simulator was better prepared this time and there was no problem running the scenarios.

3.4 The extended team work experiment [6]

The purpose of the study was to contribute with empirical knowledge on the effect of a new operational concept, implying increased automation levels, changed operator roles, redefine competence requirements to the operators, and new technologies to support co-operation, on teamwork.

In this experiment we used a VR model of about 20 rooms of Forsmark 3, and the study involved both control room operators and field operators operating in the VR model. Prior to the experiment we had to make a lot of complementing work on the simulator, specifically on the electrical side. The changes to the simulator were made by IFE personnel. The feedback from the plant crew was very positive in this experiment. Especially field operators claimed that they gained a close contact with the control room, as they could see operator displays superimposed on glasses while operating in the VR model. At the same time the control room crew could observe the field operators' whereabouts in the displayed VR model (as manekins) in the control room.

3.5 Task-based displays [7]

For some years IFE has worked with so-called task-based displays, displays specially designed for supporting operators' pre-defined tasks. Integration of procedures and operating displays was first tested in a user test in 2005, see Fig. 12 for a few example displays.

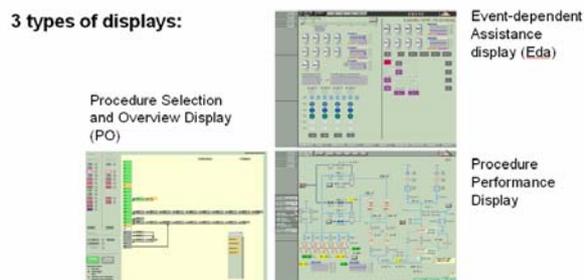


Fig. 12 Task-based displays

3.6 The ecological interface design experiment [8]

The objective of the Ecological Interface Design (EID) experiment was to demonstrate the presumed benefits of ecological displays during unanticipated power plant events. Ecological displays were compared to traditional displays in within and beyond design basis scenarios.

The project was carried out in a co-operation with the University of Toronto, Canada, the University of Waterloo, Canada and the VTT Technical Research centre in Finland.

Fig. 13 gives an example of an ecological display.

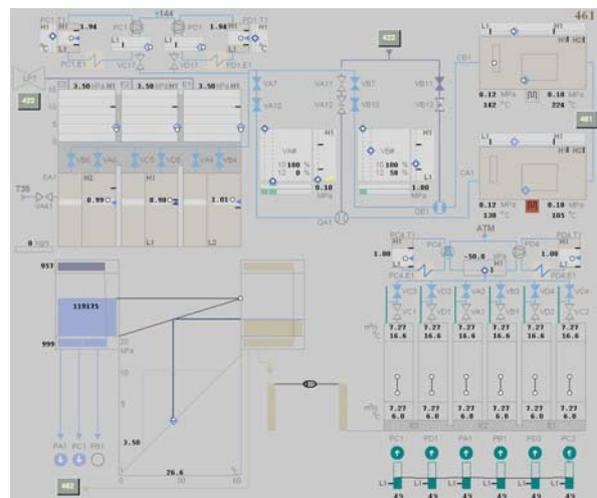


Fig. 13 Ecological displays

In the EID project a substantial amount of new signals needed to be connected to HAMBO, and even some additional modeling work on the turbine side. The APROS ACL library provided an easy access to find and connect signals.

4 Conclusions

The HAMBO simulator has been in use in the HAMMLAB experimental environment for more than five years, and numerous complex experiments have been conducted. Some of the experiments have become a real challenge for HAMBO, but so far all challenges have been met to a good result.

IFE is very satisfied with the APROS building tool and the Grades interface. We find the tools easy to use, and flexible. As the HAMMLAB simulators are used in experiments, they are continuously undergoing modifications, and the requirements to the simulator building tool are, hence, very high.

5 References

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