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DESIGN AND DEVELOPMENT OF HMI IN SIMULATOR FOR FRESH FUEL HANDLING SYSTEM

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Abstract—**KALBRSIM operator training simulator is used for training Prototype Fast Breeder Reactor (PFBR) nuclear power plant operators. In simulator, using virtual panel HMI which is an exact replica of actual hardware panels, all the essential fresh fuel operations can be done. Visualization power is also provided by 3D models which aid in quicker understanding of the complex process involved in Fresh Fuel Handling System (FFHS). Operation using Virtual Panel is an excellent tool for system developers to test the logic and process models of FFHS in KALBRSIM before integration with hardware panels. Also, operator training through virtual panel HMI can enable operator to monitor and control FFHS by running multiple screens at once at a central location. Teaching operators their effect of actions using 3D models is an add on with virtual panels which help the operator visualize the system accurately. This paper discuss the design and development of virtual panel HMI and 3D models of fresh fuel handling system used in full scope replica PFBR operator training simulator. Advantage of using HMI in simulator is also covered.**

Keywords - **Fresh Fuel Handling System, Cell Transfer Machine, CTM, PFBR, OPTS, FFHS, KALBRSIM**

I. INTRODUCTION

Prototype Fast Breeder Reactor (PFBR) is a sodium cooled, pool type, plutonium-uranium oxide fuelled, reactor with a thermal power of 1250 MWt and an electrical power output of 500 MWe[1]. Fresh Fuel Handling System is one of the important systems of PFBR as it brings in fresh fuel from the factory into Nuclear Island Containment Building (NICB). Once the fuel is unloaded, the fuel is checked and indexed. The role of simulator and the operator training begins when the checked and indexed fuel gets loaded inside the fuel building. Nuclear Regulatory Commission Regulatory Guide 1.149[2] has approved ANSI/ANS-3.5 for Selection, Qualification, and Training of Personnel for Nuclear Power Plants using Operator Training Simulators[3]. KALBRSIM, a full scope replica simulator of PFBR serves this purpose for operator training[4]. This paper deals with Design and Development of HMI in KALBRSIM related to virtual panels and 3D models used for Fresh Fuel Handling operations and visualization. The first section gives brief description of PFBR followed by hardware and software architecture of KALBR- SIM. Then it deals with introduction of FFHS followed by modeling description; this is followed by a detailed description on design and development of virtual panels and 3D models. The subsequent sections discuss integration and testing of HMI. The paper ends with discussion on advantages of HMI followed by conclusion.

II. OPERATOR TRAINING SIMULATORKALBRSIM

A. Hardware Architecture

The physical components of simulator are the simulator server, I/O computers, Control Room Panels/consoles, Instructor Panel computer, Virtual Panel computer and Intel server. The simulator computer i.e., simulation server consists of powerful mathematical models[5] which integrate with other simulator models and compute the plant dynamics. Also, the simulator computer interacts with control panel and console hardware through I/O computers and with virtual Panel computer.

Operator and the instructor interact with simulator server. Intel server consists of 3D models of the plant equipments such as fresh fuel handling system models which respond to plant dynamics and operator actions.

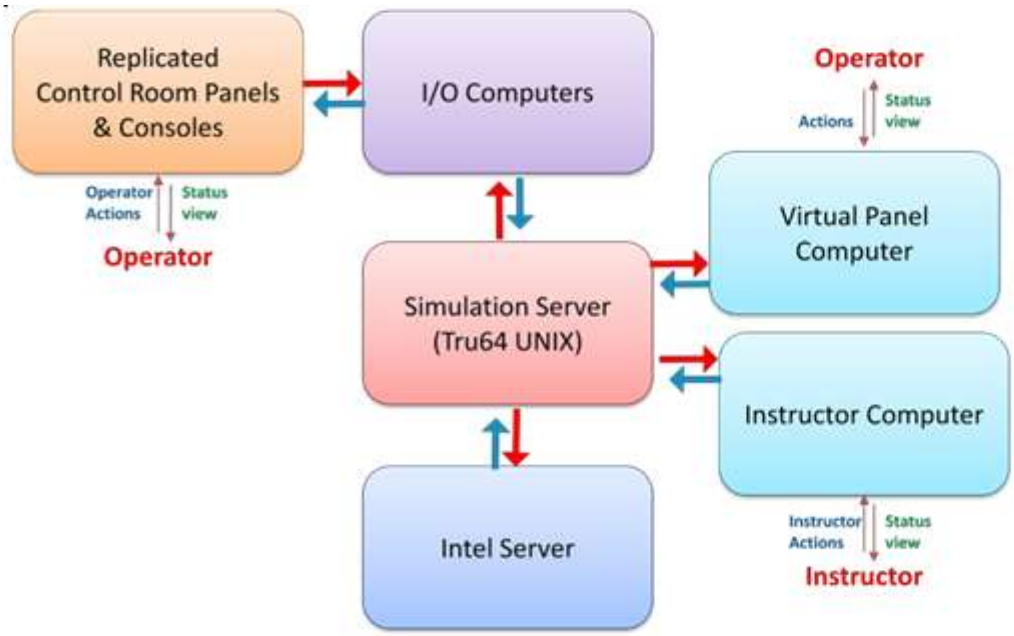

Fig. 1. Hardware Architecture

B. Software Architecture

The simulator software consists of the following components; instructor, executive, logger, database, simulation middleware, logic models, virtual panel (VP) models, process models and plant controls. The interaction between the simulator components is through message and data sharing (MDSM) mechanism, with a global database for access of data.

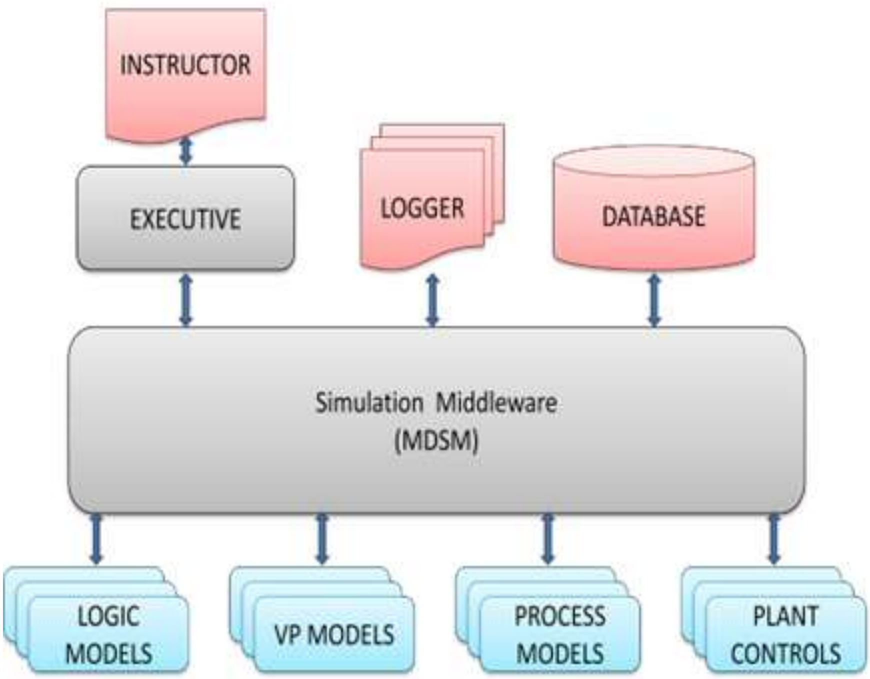

Fig. 2. Software Architecture

III. INTRODUCTION OF FFHS

Different subassemblies like fuel, blanket, reflector, shielding and absorber sub assemblies are brought to the reactor building and tested in inspection facility and stored in the storage bay. When refueling activities start, a batch of inspected SAs are transferred to the transfer chamber, which is used for transporting SA. Transfer chamber carriage is used to transport transfer chamber from loading point to another point which is below the entry port. Fresh side entry port consists of a circular opening on the floor of Fuel Transfer Cell (FTC) where a gate valve is mounted for isolating the port to make it leak tight. FTC is an inert and shielded leak tight cell; it contains fresh subassembly entry port, preheating facility, ex vessel transfer position, etc. Movement of SA within FTC is with help of a fuel handling machine called Cell Transfer Machine (CTM). Cell Transfer Machine is one of the fuel- handling machines of PFBR fuel handling system, which transfers fresh and irradiated core subassemblies within Fuel Building.

In PFBR, Fresh Fuel handling involves operation of CTM with/without Fuel Subassembly (FSA) at Fresh Subassembly Transfer Chamber (FSTC), Fresh Subassembly Entry port (FSEP), Fresh Subassembly Preheating Facility (FSPF) and Ex Vessel Transport Port (EVTP) from Handling Control Room (HCR) console /panel. In case of fresh fuel handling, the CTM transfers FSA from FSTC through FSEP to preheating facility. There are three preheating facilities and one plug storage facility namely FSPF1, FSPF2, FSPF3 and plug storage (FSPF4) facility. FSA after preheating is transferred to EVTP. From EVTP, the fresh SA is handled by Inclined Fuel Transfer Machine (IFTM) which operates remotely and safely. Using IFTM, fresh fuel assemblies are loaded into the reactor, and spent fuel assemblies get unloaded [6]. Opening and closing of FSEP and EVTP valves are also carried out. In simulator, all these operations are done through console/panel hardware buttons or through Virtual Panel HMI screens. The feedbacks are displayed either in console/panel or through HMI screens.

IV. FFHS MODELING DESCRIPTION

FFHS Development Methodology in simulator involves simulation and modeling of process, logic and virtual panel models. The process models of FFHS gets digital inputs either from panel/console by operator actions or by using virtual panel, field actions that is forced inputs in simulator is via instructor computer. FFHS external codes also get inputs from other external models in simulator such as Fuel Handling Start Up System (FHSU), IFTM system, Spent Fuel Handling System (SFHS) etc. The FFHS generates outputs with help of process and logic models. These outputs are sent back for animation of 3D models as well as indications in simulator HCR panel/console/Vpanel using I/O computers of simulator. The Fresh Fuel Handling System operation takes place when the reactor is in shutdown state. This is achieved in simulator by loading shutdown IC from the Instructor station. The context diagram is as shown in Fig. 3.

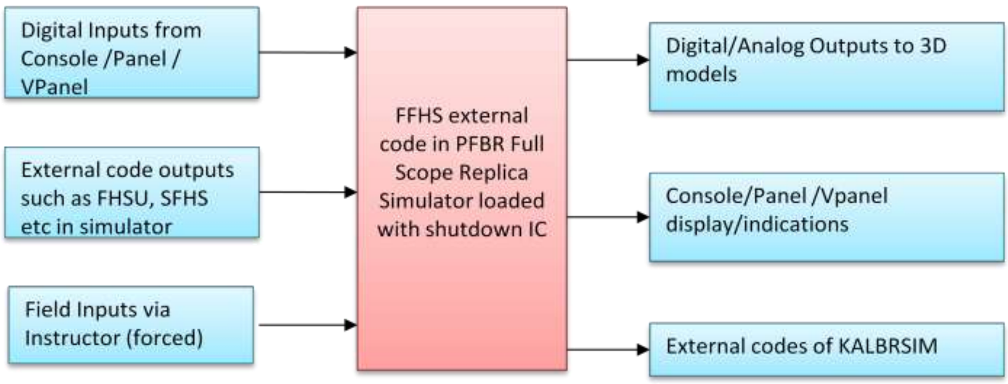

Fig. 3. FFHS Context Diagram

A. FFHS Process Functions

KALBRSIM simulator contains an external module consisting of FFHS process code. External model for FFHS was developed using C language in simulator. The model was organized to include initialization with run time block and IPC handler functions. The IPC handler was organized as follows,

- **Published Variable Function**

This function is used for registering variables for publishing into the simulator environment. The published variable is send to simulator environment for further processing/display etc. The FFHS external code triggers analog or digital outputs, when triggered these outputs will be send to other external codes via Message and Data Sharing Mechanism (MDSM).

- **Subscribed Variable Function**

This function is used for subscribing the variables needed by the FFHS model as inputs from the simulator environment for further processing. Inputs are generated either by user actions, such as operator pressing a lower/raise push button from hardware control panel/Virtual Panel or they are forced input done at field (in this case instructor station). This operator/instructor action is subscribed as input inside the FFHS external code to generate an output.

External models for FFHS are the mathematical functions which are run every cycle (200ms) in simulator. The model calculations associated with FFHS are done in process functions. FFHS process modeling involves discrete event simulation where various interlocks of the system are considered as events. FFHS system responds to interlocks and changes its output. The operations of FFHS are CTM Long Travel(LT) Operation, CTM gripper hoist operation, CTM gripper finger operation, FSEP / EVTP valve operations along with message and alarm generations.

Main functions of FFHS system include the following position calculations; Long Travel(LT) CTM position, CTM Fresh Side(FS) parking Extreme and CTM FS parking Normal, FSEP, FSPF4, FSPF3, FSPF2, FSPF1 positions, Gripper Hoist positions, SA Transfer Levels, Plug Transfer Levels, Gripper Finger Open/Close, FSEP Valve Open/Close, EVTP Open/Close etc. Preheating is carried out by depositing the SA inside the fresh subassembly preheating facility (FSPF 1 to 3) and heating it to 200 deg C. The coding is done in C language. The subscribed and published variables are in header files.

B. Logic models of FFHS

Logics and controls were modeled using simulator tool. It consists of standard libraries such as AND gate, OR gate, flip- flops, invert, latches, functional blocks etc in a standard palette. The schematic is completed by joining appropriate outputs to inputs. The logic sheet contains the controls and interlocks necessary for initiating operator actions on fresh fuel handling systems. A sample logic sheet drawn using the simulator logic tool is shown in Fig. 4.

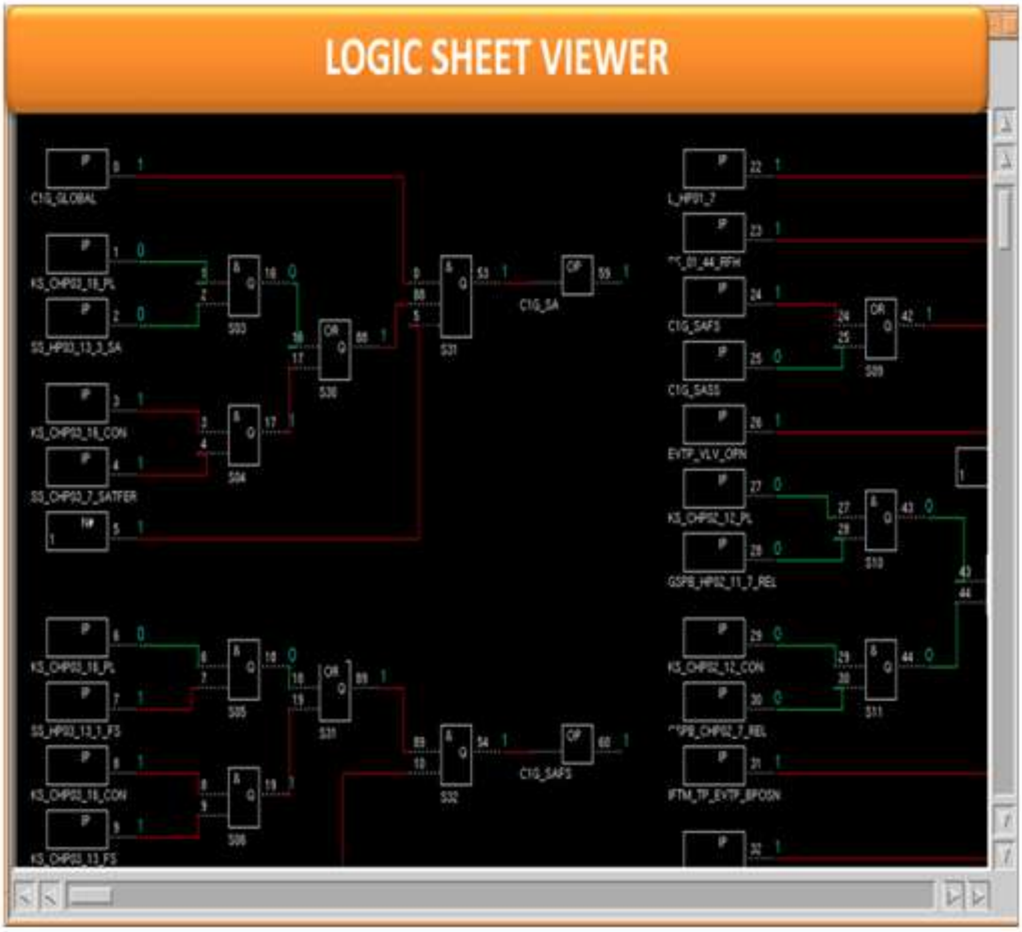

Fig. 4. Sample Logic Sheet of FFHS

Before drawing logic sheet, relevant information was gathered from various resources like control notes, design notes, etc. After thorough understanding of the system and interaction with design experts, a conceptual design was carried out followed by a detailed design. For example, for opening or closing of gripper fingers, the CTM Gripper Finger(GF) global conditions need to be satisfied as given below in Fig. 5., Key selector switch is selected from either console or panel; this can be done either through hardwired switches or virtual panel switches and the respective gripper finger selection is made using LT/Hoist/Gripper selector switch by selecting Gripper for GF operation. The following conditions also need to be satisfied: manual drive handles of Gripper Finger drive are not engaged, CTM LT or Gripper Hoist (GH) movement is not selected and CTM gripper finger overload is not present. Once the schematic of global conditions is decided then logic sheet is drawn using Logic tool of simulator.

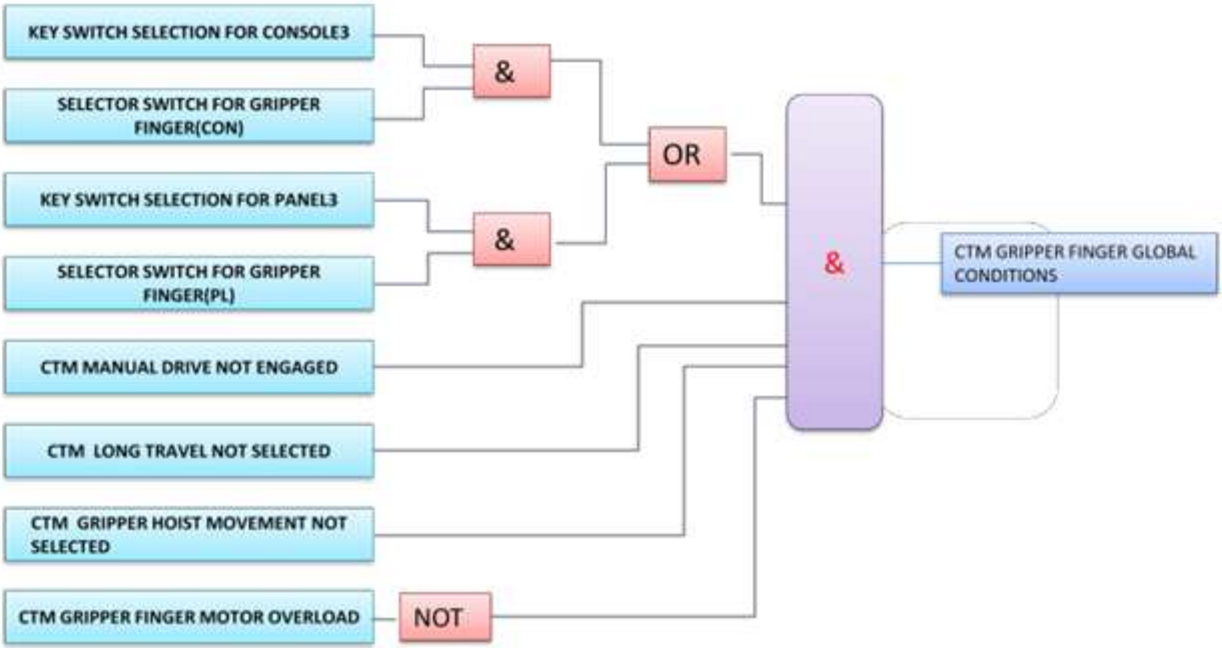

Fig. 5. Gripper Finger Logic

The sequence of operations of Fuel handling system involves checking permissive conditions, issuing the command, checking the safety interlocks, checking the feedback to ensure operation completion etc. While the simulator, KALBRSIM is running, the logic sheets can be debuggedusing instructor.

Logic Display can be used for debugging as well as for tuning of control systems. The Debug option allows the user to monitor any item in the configuration while the simulation is running and to change the values of variable.

V. DESIGN AND DEVELOPMENT OF VIRTUAL PANELS

Virtual Panel is modeled using simulator virtual panel software. Virtual Panels are interactive graphical screens for display and control[7]. Graphical primitives with fixed size and position such as line, polyline, polygon, spline etc are defined using points. A collection of primitives can be grouped and treated as single primitive, object or model and positioned in window space. For example selector switches, buttons, LED lamps etc are created, grouped and placed. In display dynamics, the screen objects /models reflect the output of the application. In input dynamics, the screen objects/models respond to mouse or keyboard events. This is achieved by attaching Dynamic Properties to the objects/models. Dynamic specifications are Model specific and performed in the application code which is in C language. Dynamic properties attached to Models are interpreted at runtime. Dynamic actions embedded in graphical icons are written in the application code to change the appearance of the object in response to changes in data variables or input events.

The soft panel is divided into three parts viz., Display, Control and Annunciation Panel and it is as per the original Hardware Panel. The display panel contains the necessary LEDs, indicators etc. The control panel consists of Control buttons, key switches etc. Annunciation panel is used to display the alarms. The relevant data for modeling

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virtual panel are collected from the designers. The Fuel handling System consists of four hardware control panels and consoles.

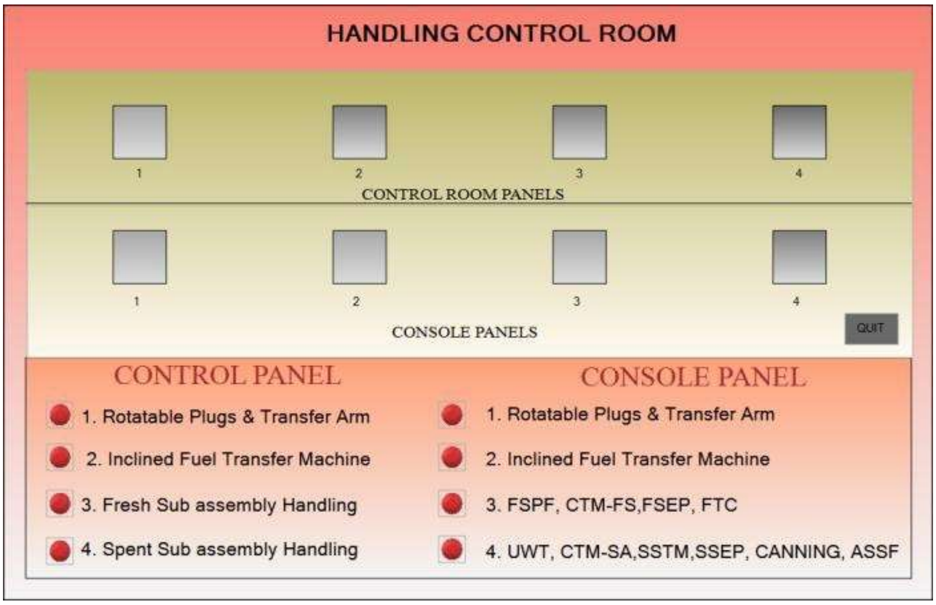

Fig. 6. Handling Control Room Layout

The same is drawn as virtual panels. They are indicated by buttons shown in Fig.6; on clicking a button the corresponding virtual panel pops up. Each screen consists of three parts: alarm, controls and indicators[8].

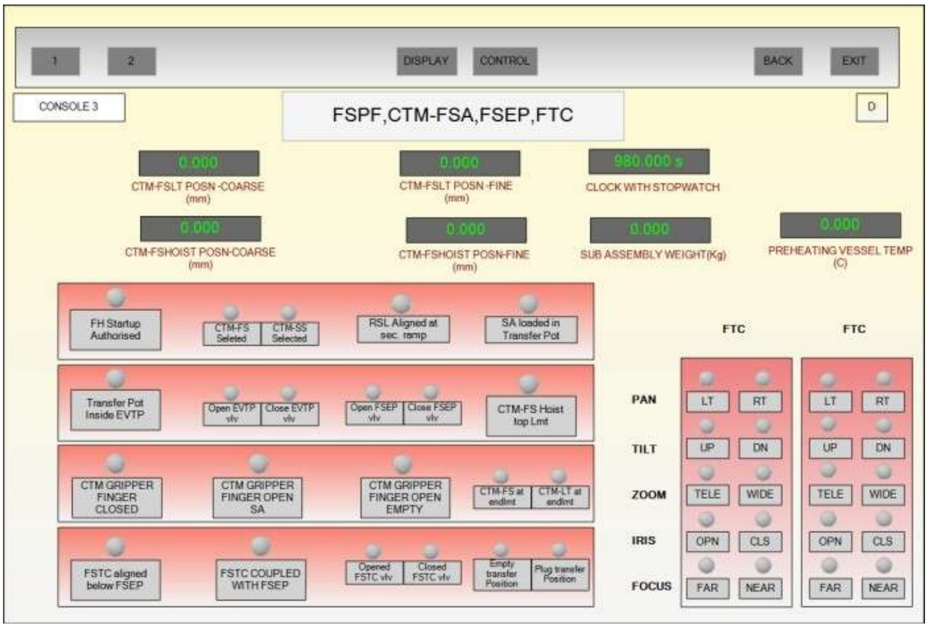

Fig. 7. VP of Console Display of FFHS

Virtual panel display and control screens of fresh subassembly console panel are shown in Fig.7. The first two rows in the display screen of fresh sub assembly handling virtual panel shows analog meters indicating coarse and fine positions of CTM-FS LT and Gripper Hoist in mm, subassembly (SA) weight in Kg and Preheating Vessel

Temperature in Degree C. Apart from this, there is a clock with stop watch indication too. CCTV camera parameters such as pan, tilt, zoom etc in fuel transfer cell are also shown. Various operational LED indications of CTM shown in the virtual panel are FH startup authorized, CTM-FS/SS selection, Rotatable Sheild Leg (RSL) alignment at secondary ramp, etc.
Color, diffuse color, specular color, emissive color, shininess and transparency, underwent changes.

B. **Scene Graph Modeling**
The scene graph was written using C++ programming. Scene graph consists of root with children. The root also contains camera with light. The following children were modeled: Fuel Subassembly (FSA), Fresh Subassembly Transfer Chamber (FSTC), Fuel Transfer Cell (FTC), Fresh Subassembly Entry port (FSEP), Pipelines connected to FSEP, etc. in FTC, Fresh subassembly Preheating Facility(FSPF), Fresh subassembly Vessel Plug, CTM Gripper Hoist, Gripper Fingers, EVTP, Valves: EVTP/ FSEP. The components were placed in scene graph with respect to Ex Vessel Transfer Port with the distance as per the actual component placement. The scale was matched as per the design drawing. The centre of the viewing window was placed at (0,0,0) Cartesian co ordinates and the nodes were distributed accordingly. A representative figure of scene graph is shown in Fig.9. The main models alone are shown in the figure.

Fig. 8. VP of Console Control of FFHS

The various control buttons modeled in virtual panel for console control are; selector key for choosing console(CON), panel(PL)or LCC, sequence selector for choosing Computer guided, Manual or Maintenance modes, FSEP selector, CTM- FS/SS selector etc. These are 3-way, 4- way or 7-way selector keys.
Similarly the panel also has Panel control and Panel display virtual panels developed.

VI. DESIGN AND DEVELOPMENT OF 3DMODELS

The 3D models and animation was developed in house using platform independent C++ code with OpenGL based APIs. The 3D modeling code includes C++ headers and Computer Aided Three-Dimensional Interactive Application

(CATIA) models. Most of the 3D models were inherited from CATIA models. The other complex 3D models that were necessary for the successful operation of the fresh fuel handling system simulator were developed in C++, using indexed face/line set, triangle strip set, NURBS curve/surface and mesh APIs. The steps involved during modeling are given below,

A. **Data Collection**

All the CATIA files including catpart as well as catproduct were collected. Around 300 numbers of CATIA files were converted to Open GL compatible files. The converted files are made up of default material. These materials were programmed to change the colours, transparency and texture as required. Several properties of material such as ambient

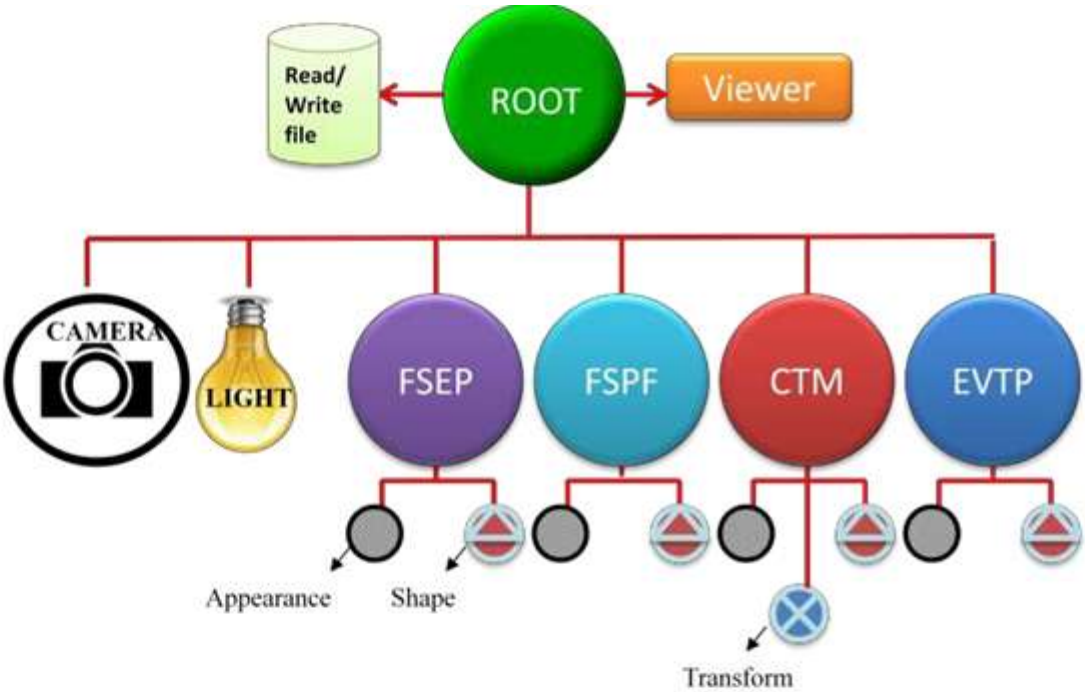

Fig. 9. Scene Graph

Constructive Geometry Modeling was carried out for modeling walls; with difference operator CSG Operation ("A- B"). The Light model used is Phong model. A camera node generates a picture of everything after it is placed in the scene graph. The camera was placed near the top left of the scene graph, since it must precede the objects. The type of camera used is Perspective camera which emulates the human eye i.e., objects farther away appear smaller in size. The following were used while modeling camera viewport mapping, position, orientation, aspect ratio, near distance, far distance and focal distance. The camera position and orientation was changed at FSEP and EVTP valve opening/closing and Gripper hoist movement at EVTP.

C. **Modeling of kinematics and rigid body transformation**

The kinematics of the assembly of various models as well as the various transformations of the individual components were modeled to perform translation, rotation, etc. These actions are required for the components to perform the operation based on control inputs. Hence components which need to perform dynamic actions and which need to be animated were identified and soft sensors were attached to it.

The components animated were;

- CTM gripper hoist up/ down movement
- CTM gripper finger open/close
- CTM Long carriage Left/Right travel
- FSEP open/ close
- EVTP valve open/close
- Vessel plug horizontal and vertical travel movement
- Fresh subassembly horizontal and vertical travel movement

The various nodes in the scene graph contain information stored in fields (for example position information). Data and timer sensors attached with the node watch for a particular type of event and invoke a user defined callback when these events occur. Whenever the callback function executes, the function accesses the trigger field. For example, when FSEP valve needs to be opened from closed state, translation movement gets triggered as the timer gets scheduled. The opening function is attached to scene graph database, on completion the timer gets unscheduled and it stops. Whenever the operator press or clicks open button of FSEP valve from HCR panel/console/VPanel the action triggers the opening. Fig.10 shows CTM 3D models consisting of CTM-FS, FSEP valve, etc.

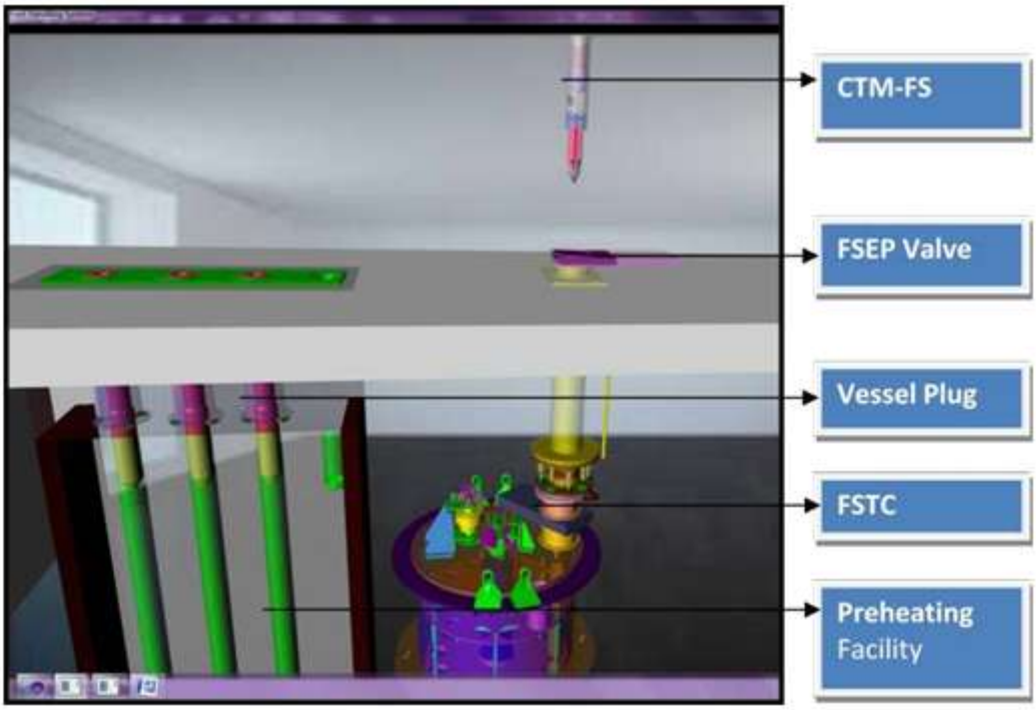

Fig. 10. CTM 3D models

VII. INTEGRATION AND TESING OF FFHS HMI

The simulated data in FFHS process is sent to hardware/virtual panels and display stations. Similarly, the hardware/virtual panel inputs are received by an external code written for panel input/outputs. This command data is published by that external code to MDSM which in turn is subscribed by the FFHS external code[9]. FFHS virtual panel was integrated with this external code along with logic models and tested thoroughly by forcing inputs and viewing the output behavior. All the three models along with the FFHS external model is in Tru Unix -64 Environment residing in simulator server and is connected to FFHS 3D animation system which is in Windows environment through UDP socket. In the simulator server, the 3D FFHS signals are received using non blocking UDP receive function. The received data is then distributed among other internal simulator models through shared memory based publish/subscribe communication mechanism[10]. The 3D models being a multi threaded application, the UDP communication with simulator server is handled by one thread. The other tasks such as scene rendering and computation of FFHS parameters and animation of 3D models are carried out by the other threads. All these threads are synchronized using global variables. After 3D models are successfully integrated, normal operation or malfunction initiation from instructor station is carried out with commands issued through virtual panels and it is tested for the reflection in the animated HMI with their corresponding behavior verification.

VIII. ADVANTAGE OF HMI IN SIMULATOR

Need for training operators using simulator is mandatory before actual operation in nuclear plant[11]. Hence system developers of simulator need to design and model virtual panel HMI. The need for virtual panels for system developers is for testing their developed system quickly and efficiently. As and when demand is there for change in the system, they can quickly model and test it thoroughly using virtual panel before integration with hardware panels.

Operator training is a two stage process, first the operator gets trained using virtual panel to quickly learn the concepts and then gets training using the hardware panels. By using virtual panel, the operator can quickly grasp/learn how his actions affect the plant as he is able to control and monitor the fresh fuel handling system at a single central location by using multiple screens suiting his operation or sequence of tasks. Hence, this will be a stepping stone before the operator starts using the actual hardware panel in Simulator Control Room as well as in Main Control Room in Plant. As the virtual panels are exact replica of the hardware panel, operator is comfortable when there is a switch over. The main advantage of virtual panels is it being a quick and a cost effective learning tool[12]. However training of operators using virtual panel is not mandatory as there are Replica Hardware panels available for training in simulator Handling Control Room. Advantage of 3D models are when an operator operates from handling control room, the consequence of his actions gets reflected in 3D models which ensures that the operator learns. FFHS is a sequential and time consuming complex operation.

Some of the operations which the operator has to perform, such as valve opening/closing or movement of CTM from one place to another have to be inferred through analog or digital values only. These values are seen as LED lamp indications, Digital meters, alarms, etc. As visualization is a powerful medium 3D models aid the operator by providing clarity in their operations. For example, when CTM raise operation is involved, on clicking raise button from hardware or virtual panel, if all the global conditions are satisfied, CTM starts raising, this can be seen by glowing of raise LED and position sensor values indicated in analog meter. As an add on, the operator can also see raising of CTM in 3D model. The skill set of the operator gets enhanced as the operator action gets visualized.

IX. CONCLUSION

Operator training is a must before commissioning of any plant. Full Scope Replica Simulator of Prototype Fast Breeder Reactor aims in providing operator training in fuel handling systems. Advantage of HMI is manifold, not only it is cost effective and easy to use but also it provides realistic view for control and monitor. An operator can operate and monitor the machine from the HMI. This may include information like temperature, pressure, process steps, sequence and time information etc. HMI can also show very precise levels of opening/closing of valves, exact positioning of machines etc. Wherever machine or equipment information is to be viewed on multiple indicators or hardware panels, now it can be viewed on HMI screens with just button clicks. System developers as well as plant operators can control or perform the operations from a central location. Most of the reactor machines/equipments are kept at far or remote places. 3D models help the operators, as they need not approach areas or places where the actual equipment is kept. An operator action that is the machine control gets reflected in the 3D models of the equipment. Hence there is an easier overall understanding of the plant in a better way. This paper focuses on HMI modeling, which aids the system developer and operator in operation, improvement and visualization of fresh fuel handling system. The Human Machine Interfaces (HMIs) for the operator, both the virtual panel and 3D has been designed such that the operator can get suitably trained with better understanding and clarity.

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