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Research Article

A Conceptual Framework for Equipment Maintenance Automation under a Pyroprocessing Automation Framework

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For most of the remote maintenance activities of equipment in a hot cell, replacing breakdown modules is preferred over in situ repair because of insufficient space in the cell and the limited operability of remote handling tools. In such cases, the maintenance operation can be decomposed into transport of the new modules to the failed equipment, replacement of the broken modules with new ones, and then transport of the broken parts to the reserved space for further repair or disposal. In this respect, transfer is the most basic operation during remote maintenance, which is also true for the maintenance of pyroprocessing equipment. Hence, this paper proposes a maintenance automation framework for automated pyroprocessing equipment from the standpoint of module transfer. For the maintenance automation framework, maintenance-related functions and events are defined, and they are integrated with the pyroprocess automation framework. The proposed framework is verified by a case study on the maintenance of a large module through a hardware-in-the-loop simulation.

1. Introduction

Pyroprocessing is a technology that reduces the volume and toxicity of spent nuclear fuel that uses electrolysis with high-temperature molten salt. In these electrochemical processes, the material from nuclear fuel is transmuted into a metal form by an electrolytic reaction with electrodes. The group of transuranic elements is recovered and distilled for reuse. Korea Atomic Energy Research Institute (KAERI) has been studying the pyroprocessing technology and developed PRIDE (PyRoprocessing Integrated inactive DEmonstration facility) for studying integrated engineering scale pyroprocess performance and scale-up issues using depleted uranium with surrogate materials [1–3]. PRIDE has an argon cell where the oxygen and moisture level are controlled within 50 ppm. In the argon cell, major process units such as the electrolytic reducer, cathode processor, electrorefiner, salt distiller, liquid cadmium cathode type electrowinner, residual actinide recovery apparatus, cadmium distiller, and waste molten salt treatment apparatus were installed [1]. In addition, auxiliary apparatuses for basket replacement or material distribution have also been developed to support the integrated processes.

Integrated processes at PRIDE are carried out by sequentially transferring the process material contained in baskets to the next equipment. The transfer of baskets between equipment during the processes is carried out by remote handling devices such as mechanical master-slave manipulators, cranes, or bridge-transported dual arm servo manipulators [2]. As a result, the progress speed of the process depends mainly on the skill of the operator, which means uniform process quality control is difficult to achieve. Moreover, as the capacity or number of items of equipment increases, there is a limitation depending only on conventional manual operations, since the conventional remote tools do not have sufficient workspace, degrees of freedom, and payload. The exposure time of the workers can also increase. In these circumstances, automation of the pyroprocess is a possible solution, and an automation framework for pyroprocessing based on material transfer automation was proposed for automating integrated processes [4]. However, there has not been a great deal of research on the automatic control of integrated processes with multiple equipment. In previous studies, automation in radiation environments such as hot cells mainly focused on the automation of unit equipment or handling devices that use robot systems in order to increase the workers' safety during routine processes and to reduce the errors caused by workers [5–7].

On the other hand, the remote maintenance of process equipment that operates in hot cells should be considered in cases of failure. In general, when equipment failure occurs, maintenance operations based on replacement are preferred to in situ repair due to insufficient workspace in the hot cells and the limited operability of remote handling tools. In this case, remote maintenance is performed in the following order: (1) New modules are brought into the hot cell. (2) They are then transferred to the broken equipment. (3) The failed modules are replaced with new ones. (4) The failed parts are transferred out of the cell. Hence, maintenance tasks can be interpreted as the sequential transport of modules. This means that automation of maintenance can be achieved in a similar way with material transfer automation if the replacement operation is simplified. Upon this background, this paper proposes a concept of maintenance automation in hot cells from the viewpoint of module transfer automation. For this purpose, the functions and events for automating module maintenance have been defined taking into account the pyroprocess equipment characteristics, and they are integrated with a pyroprocessing automation framework [4]. Maintenance-related functions specified in the automation standards are also considered in the proposed framework. In order to verify the possibility of the proposed concept, a hardware-in-the-loop simulation environment is developed, in which equipment and cell resources necessary for maintenance operations are virtually implemented. A case study shows the feasibility of the proposed concept.

This paper is organized as follows. Section 2 reviews the pyroprocessing execution system (PES), which is a pyroprocessing automation framework, and Section 3 addresses the proposed maintenance automation concept and considers the integration of the concept with PES. Section 4 presents the results of a case study for maintenance automation in the pyroprocess.

2. Automation Framework of Pyroprocessing

Since the pyroprocess is a batch process in which the material flows and the basket transfer are closely related, the concept of automating the pyroprocess that links the transfer tasks of baskets with the progress of the process has been presented. Ryu *et al.* analyzed the transfer routes of the pyroprocess with respect to material flow and classified pyroprocesses into process blocks in which the same baskets can be used [8]. In addition, based on the material transfer relationship between the equipment or between the process blocks, studies on the equipment layout for automated pyroprocessing have been performed [9, 10]. In addition, the PES as a pyroprocessing automation framework was proposed in order to control the automated integrated pyroprocessing operations and to manage the material flows during the process [4].

2.1. Pyroprocessing Execution System [4]. The manufacturing execution system (MES) is a control execution system for automated production presented in the international standard, ISA-95 [11]. The MES includes level 3 functions for manufacturing operations management systems such as production planning, production execution, operation management, and production management. The PES implements the system of the MES into pyroprocessing automation. For this purpose, the MES' functions were modified to apply them to the pyroprocessing. As a result, the PES can perform the control of integrated process operations through basket transfer automation and also can conduct the systematic lot management by tracking material flow such as the creation, distribution, or merging of materials during processes. Figure 1 shows the functional architecture of the PES and the messages exchanged between those functions.

The PES receives process plans from a higher planning level and schedules and arranges the detailed orders based on the plans. The detailed schedules are transmitted to a lower control level such as block controllers for process equipment (pEC) and block controllers for material handling equipment (mhEC). During the given tasks performed by the process and handling equipment, the block controllers report the results to the PES whenever noticeable events occur. The PES manages and monitors the entire workspace by using the event's messages and sends some information to the higher layer.

Pyroprocessing is a static process whose sequence does not change frequently, and its production rate is generally stable. As a result, the process plans will be simple, but the detailed operation orders can be more complex because the orders should be scheduled under simultaneous consideration of the process plan, raw process materials, work-in-process (WIP), and the availability of all equipment.

For this purpose, in PES, the Pyro-DSP (pyroprocessing dispatcher) schedules and arranges the detailed orders based on the predefined dispatch rule, shop-floor status, and material handling requests (MHReq) for the basket loading or unloading sent from the pEC. The detailed orders are then sent to the pEC and Pyro-MCS (pyroprocessing material control system) simultaneously, and the pEC commands the relevant process units to prepare for the handling operations and the Pyro-MCS commands mhEC to perform the tasks. According to the commands, material handling equipment transfers the process baskets from the equipment of one process to that of another. During this operation, the material handling equipment can communicate with the process equipment to check and confirm the basket identification to be handled. After the transportation is completed, the material handling equipment reports the command results, and the process equipment informs the start of the process.

The PES monitors the status of workspaces by using a WIP manager (WIP manager) and equipment manager (EQPMgr). All information related to material handling during the process is stored and tracked by the material

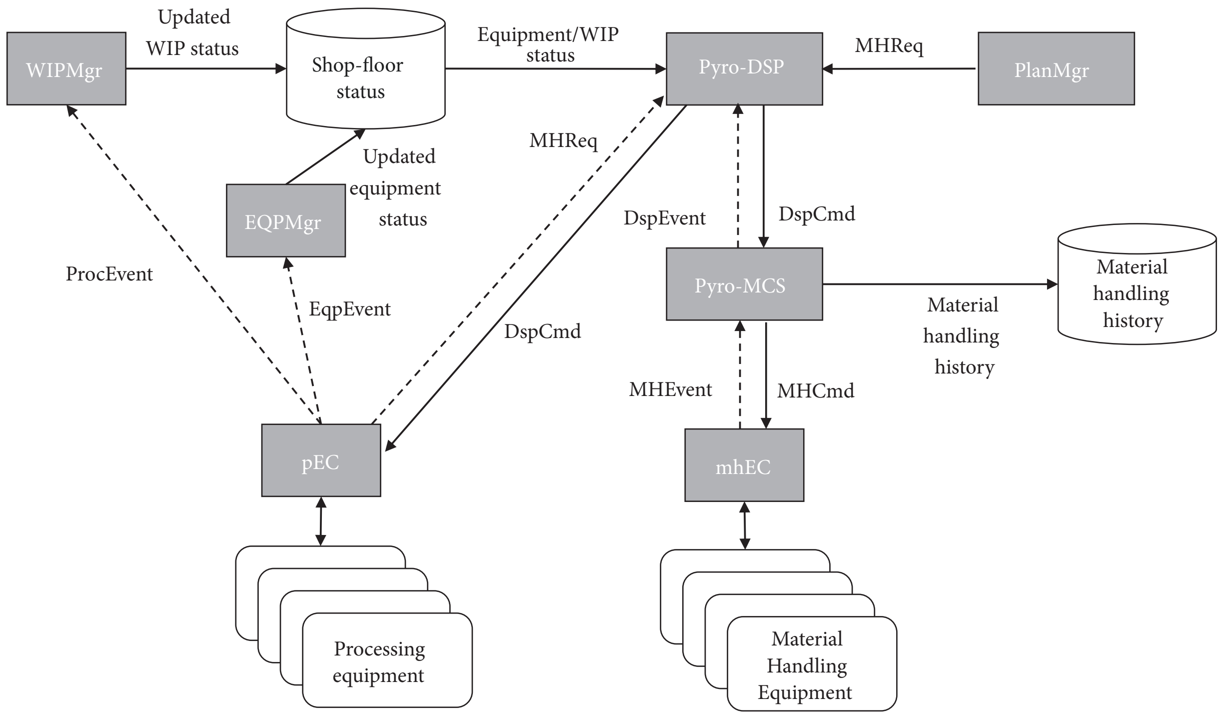


Figure 1: Functional architecture of the pyroprocessing execution system [4].

handling history. The information includes the event's name, date, container information (identification of current and previous baskets), WIP information (identification of lot, product, and process), and moving paths (current equipment and destination). This information can be used to track and analyze the material's history and control the product quality.

3. Conceptual Framework for Maintenance Operation Automation

In general, the maintenance of equipment that operates in a hot cell takes more time since a human operator cannot access the equipment directly and the performance of the available remote handling tool is not sufficient. For this reason the development of equipment to be operated in a hot cell primarily focuses on the operability and maintainability of the remote handling equipment. For example, International Thermonuclear Experimental Reactor (ITER) utilizes a remote maintenance management system that monitors and maintains equipment during its life cycle, and the system also emphasizes the remote compatibility of equipment with remote handling devices [12].

On the other hand, in the general manufacturing industry, maintenance is closely related to process planning since equipment failure directly affects the production rate. Hence, computerized maintenance management systems have been applied in order to reduce the downtime of equipment and manage maintenance schedules and resources efficiently [13]. Similarly, ISA-95 also defines the required activities and information for maintenance operations management at an MES-level, as shown in Figure 2 [11]. These functions for managing maintenance instruction and required devices, maintenance capability, maintenance history, and so on are also required for pyroprocessing automation so that maintenance operations are systematically controlled.

3.1. Equipment Model for Automated Pyroprocessing. Since maintenance operations depend greatly on the equipment, a specified equipment model is required for maintenance automation. The main equipment of pyroprocessing uses electrochemical reactions between the electrodes and materials contained in a basket in a molten salt bath. Because of this, it is common that electrodes and baskets are inserted into the vessel from above. Therefore, the general structure of the equipment has a stacked form with a heater, react vessels, and cover for heat shields on a frame. In addition to the insert slots, the heat-shielded cover can have additional mechanical structures for lifting electrodes and baskets or utility modules for off-gas treatments.

In order to maintain this stacked equipment remotely, it is advantageous for remote handling equipment to access the equipment from above. When one module is transferred during a maintenance operation, the modules stacked above are also transferred. From this observation, it is possible to generate a work order in order to maintain modules automatically.

As shown in Figure 3, this study adopted the class diagram of the unified modeling language (UML) to define the equipment modules systematically. Since this equipment module model is based on the physically replaceable module, this model is not exactly the same as the equipment model in ISA-88, which is based on the functional module [14]. The

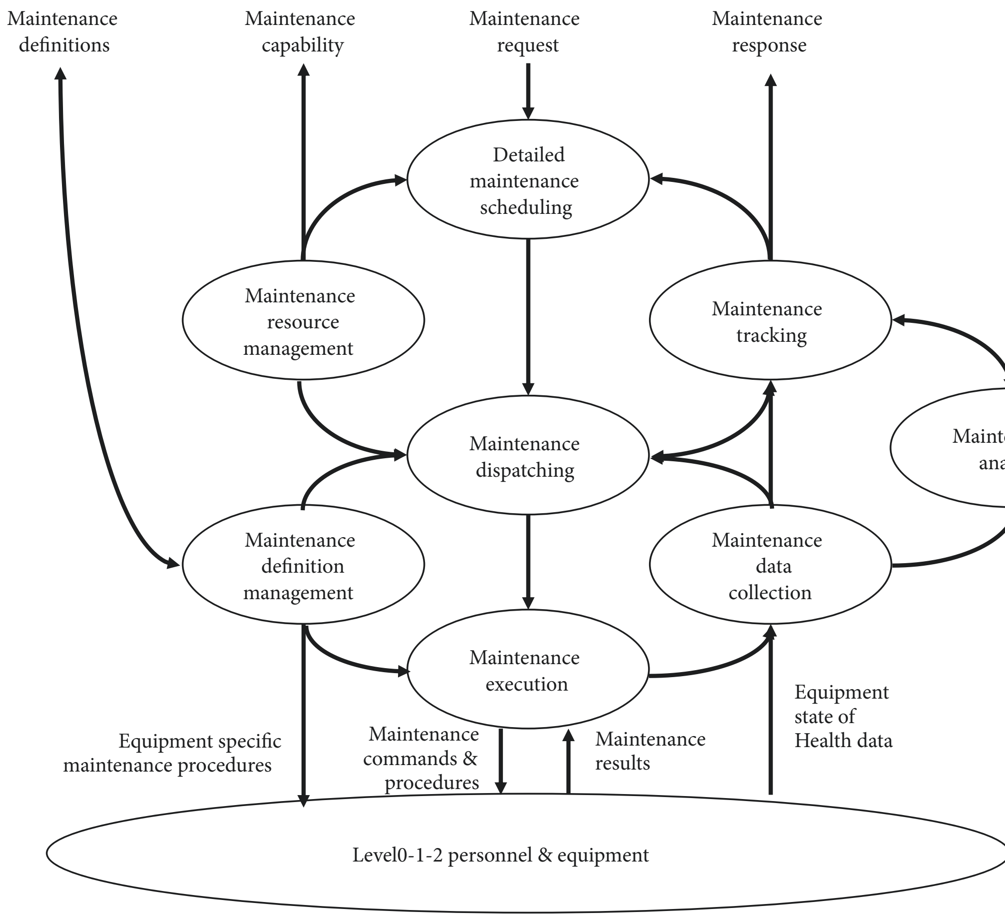


Figure 2: Activity models of maintenance operations management [11].

Equipment module Name
+Equipment
+ID
+State {Status, Event code, Date}
+Maintenance {RH equipment, RH tool, RH class, Installation date, Expected life}
+Parent {ID, location}
+Children {No. of children, ID of child 1,...}
+Operation()

Figure 3: Equipment module using UML class.

attributes for a module have items about equipment, identification, and status of the module, as well as maintenance-related information and parent and child modules. The maintenance-related information includes remote handling (RH) equipment and tools, RH class, installation date, and expected life. The RH equipment and tools are assigned to consider the module's weight, sizes, and mechanical interfaces. The RH class is determined based on the maintenance period and safety, as shown in Table 1 [15, 16]. It can be noted that the expected life for preventive maintenance can be used to plan the material handling schedule, whose period corresponds to the life.

Each module can have a parent module and one or more child modules, and the relation between those modules can be defined as composition or aggregation. If two modules have a composition relation, both modules should be transferred together during the maintenance operations. If they

Table 1: Remote handling (RH) classification for process equipment maintenance.

RH classification	Maintenance
Class 1	Periodic or preventive
Class 2	Unscheduled maintenance when failed
Class 3	Not required, but safety related part
Class 4	Not required

Table 2: Implementation of maintenance operations management functions in PES.

Functions	Operations	Implementation in PES
(i) Maintenance definition management	(i) Work order management	(i) WDMgr added
(ii) Maintenance resource management	(ii) Management of resources (equipment, tools, and spaces) for maintenance	(ii) In Shop-floor status, EQPMgr and WIPMgr. WIPMgr expanded to RSCMgr
(iii) Detailed maintenance scheduling	(iii) Planned/preventive maintenance request	(iii) In PlanMgr
(iv) Maintenance dispatching	(iv) Maintenance request review, approval, and dispatch	(iv) In Pyro-DSP
(v) Maintenance execution	(v) Perform maintenance	(v) In Pyro-MCS
(vi) Maintenance data collection, Maintenance tracking, and Maintenance analysis	(vi) Manage maintenance result	(vi) In material-handling history

have an aggregation relation, they can be transferred individually. Therefore, these relations can be used to generate a work order for modular equipment maintenance systematically.

3.2. Maintenance Concept under PES. When operating equipment in a hot cell is broken, the equipment is maintained by replacing the fault modules rather than fixing them directly, since the spare space is not sufficient, and the operator cannot access directly. The replaced parts are decontaminated in a separated space before they are repaired by a human operator or disposed as waste [17]. A similar method can be considered as a maintenance method of the pyroprocessing equipment. In this case, maintenance in a hot cell is carried out in the order of bringing in new modules, transferring them to the faulty devices, disparting faulty modules, installing new modules, and transferring out the faulty modules. Except for the replacement, most of the maintenance operations consist of transferring modules. In the case of preventive maintenance, it can be regarded as handling material that has a relatively long handling cycle, but is considered a high priority. Thus, maintenance tasks can be interpreted as a series of module transportation tasks, and therefore maintenance operations can be automated in a similar way as process automation. In other words, the equipment module is automatically maintained in the same manner as the baskets that are transferred automatically during the pyroprocess.

To automate the maintenance operations under the PES, the activity models for maintenance operation management defined in ISA-95 (Figure 2) should be considered. Since the replacement of modules in maintenance is basically similar to the automated transfer of process material, most of the activity models can be managed by the PES functional architecture shown in Figure 1, except for maintenance definition management and maintenance resource management activities. Hence, WDMgr and RSCMgr for those activities are implemented respectively into PES. Moreover, a block controller for the cell equipment (rscEC) is added, which controls the cell ports that bring a new module into the cell and transfers them out during maintenance. The updated PES functional architecture for maintenance automation is shown in Table 2 and Figure 4.

In addition, ProcAbort as a maintenance-related event has been added in addition to the EqpDown event when a process is interrupted by the equipment breaking down. When a ProcAbort event occurs, an event message is transmitted from the pEC to the RSCMgr. The PES then checks the inventory for modules and generates the maintenance work order. The internal messages exchanged in the PES include the information of the failed equipment (EqpID), the modules to be transferred (ContID and LotID), and the handling equipment for maintenance (mheID). Identification is assigned to the maintenance process (ProcID = FIX). EqpID and ContID can be used as error codes to be reported.

4. An Example Implementation of the Maintenance Automation Concept

A case study was performed to verify the performance of the proposed remote maintenance automation concept. In this case study, a reaction vessel was maintained as a large module within a hardware-in-the-loop system (HILS) that was developed using Siemens Tecnomatix [18].

4.1. Virtual Pyroprocessing Hot Cells. A virtual environment for this study was built to simulate an automatically operated pyroprocessing hot cell. As shown in Figure 5, the virtual hot cell was divided into two areas, (i.e., a process operation area and an in-cell maintenance area), so that the maintenance operations can be performed safely in a separated space without any interference from operations in the process operation area. Moreover, the repaired equipment can be tested in the space before it is moved to the process operation area for operation.

In the process operation area, various conceptual designs of the pyroprocess equipment and support equipment were implemented for process automation studies. Cell equipment such as transfer ports and auxiliary equipment were placed in the in-cell maintenance area. In addition, remote handling equipment for process operations and maintenance that can be covered inside this hot cell were also considered.

As mentioned, since the main pyroprocessing equipment has a stacked form, it can be modularized to be assembled

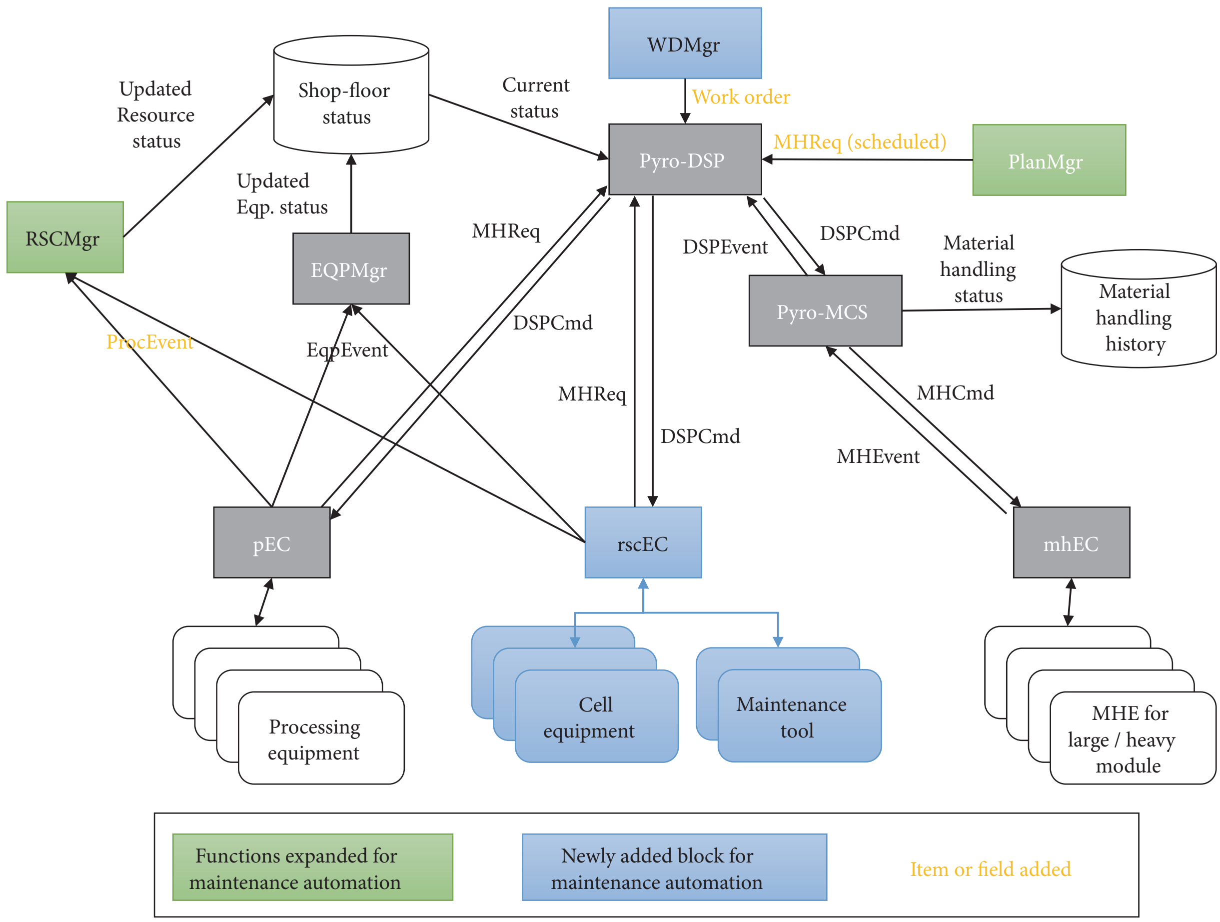


FIGURE 4: Upgraded PES functional architecture for maintenance operations.

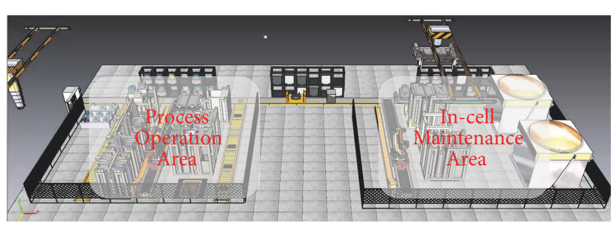


FIGURE 5: Virtual pyroprocessing hot cell.

from above using remote handling equipment. Each module has a physical interface, which is compatible with the handling equipment, and it is assumed that the electricity or utilities are connected automatically when the module is installed on the parent module. Figure 6(a) shows a modeling example of the pyroprocess equipment in the virtual hot cell, and Figure 6(b) indicates the corresponding UML class diagram of the equipment.

In this equipment model, the vessels were put on the frame, which is equipped with a heater. In a similar way, a heat-shielded cover was installed on the vessels. It can be said that the relation between the reaction vessel and the heat-shielded cover is composition, since the cover is installed statically on the vessel, and the vessel cannot be replaced without removing the cover. On the other hand, baskets and electrode modules have an aggregation relationship with the cover because they can be transferred to other equipment frequently during the process. As a result, they may not be transferred with the cover during the cover's maintenance. By considering these relationships between the parent and child modules, the work order for maintenance can be managed systematically.

4.2. HILS for Pyroprocessing Automation Study. Figure 7 shows the structural diagram for verifying the process automation and maintenance automation performance. This HILS is composed of a PES and block controller, hardware with a programming logic controller (PLC) for equipment

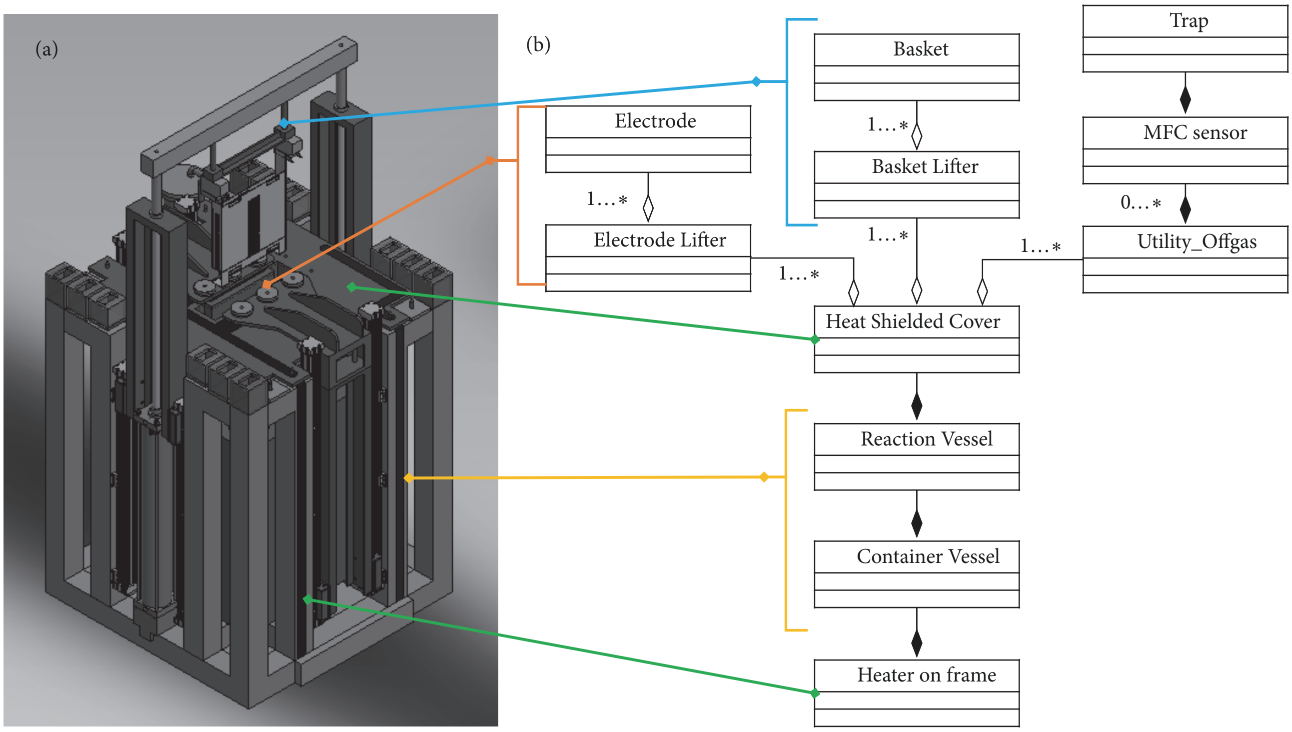


FIGURE 6: Equipment model. (a) An example of process equipment and (b) UML model.

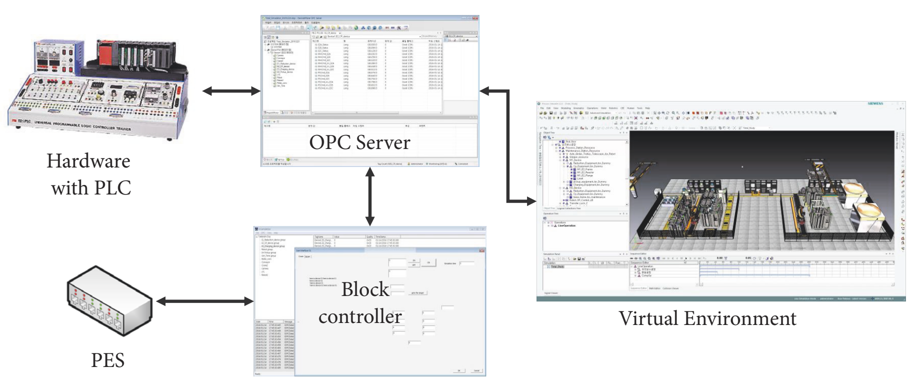


FIGURE 7: Hardware-in-the-loop simulation system for pyroprocessing automation study.

control, and a virtual pyroprocessing hot cell. In the virtual environment, 3-dimensional models for automated process equipment, handling equipment, cell equipment, inventories, and controllers are realized. Some signals and actions required for equipment control in the virtual hot cell are linked with the hardware user interfaces such as push buttons, motors, and limit switches. The PES and block controller can command and monitor both the virtual environment and hardware for automation studies. Each system in the HILS communicates via an OPC protocol.

In simulations, the PES and block controller managed the integrated processes. When an event signal was triggered through hardware user interfaces during the process, the signal was transmitted to the block controller and PES via an OPC server. The PES then generates process schedules or a work order, including material handling commands, and the block controller sends the schedules to the virtual environment and hardware. After the given tasks, the real hardware devices and virtual equipment report the results to the block controller. In such a sequence, this HILS can be used to verify the automated operations, including maintenance.

4.3. A Case Study for Maintenance Automation. Using the HILS, a case study was performed to verify the proposed maintenance automation concept. A fault event for process equipment can be created by an operator using hardware user interfaces, and the PES and block controller receive the event's message through the OPC server. The PES then generates work orders for maintenance based on error codes in the message, and the block controller sends commands

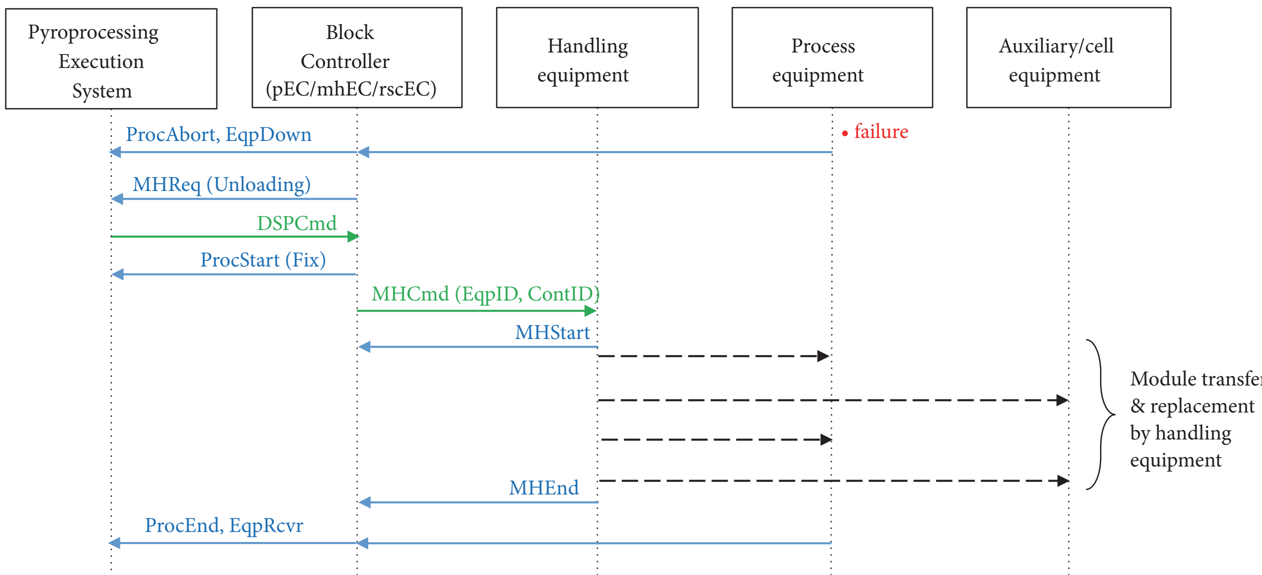


Figure 8: Simplified sequence diagram for automated maintenance operation.

sequentially to the process equipment, material handling equipment, and cell equipment. Material handling equipment communicates with the process equipment and cell equipment to check and confirm the module to be replaced. Figure 8 shows a simplified sequence diagram for these maintenance operations.

As an automated maintenance scenario, it was assumed that a reaction vessel filled with molten salt failed, for example, when a crack was found on the vessel wall. In a real system, when the equipment is broken down, the pEC informs the EQPMgr and RSCMgr of this fault event. Instead, in this study, the event was generated when a button on the hardware user interfaces was pressed by an operator. The signal was then updated when the event updated the related memory on the OPC server. Referring to the OPC server, the block controller sent the event messages about the fault to the PES and also requested the maintenance (MHReq for unloading the failed part). The fault event was visualized in the virtual hot cell (the color of the equipment changed, as shown in Figure 9(a)). The PES then creates a work order for the reaction vessel replacement by using the handling equipment for large modules. According to the order, the block controller commands the related process equipment, handling equipment, and cell equipment sequentially in the virtual hot cell. Figure 9 shows all of the maintenance procedures of the reaction vessel.

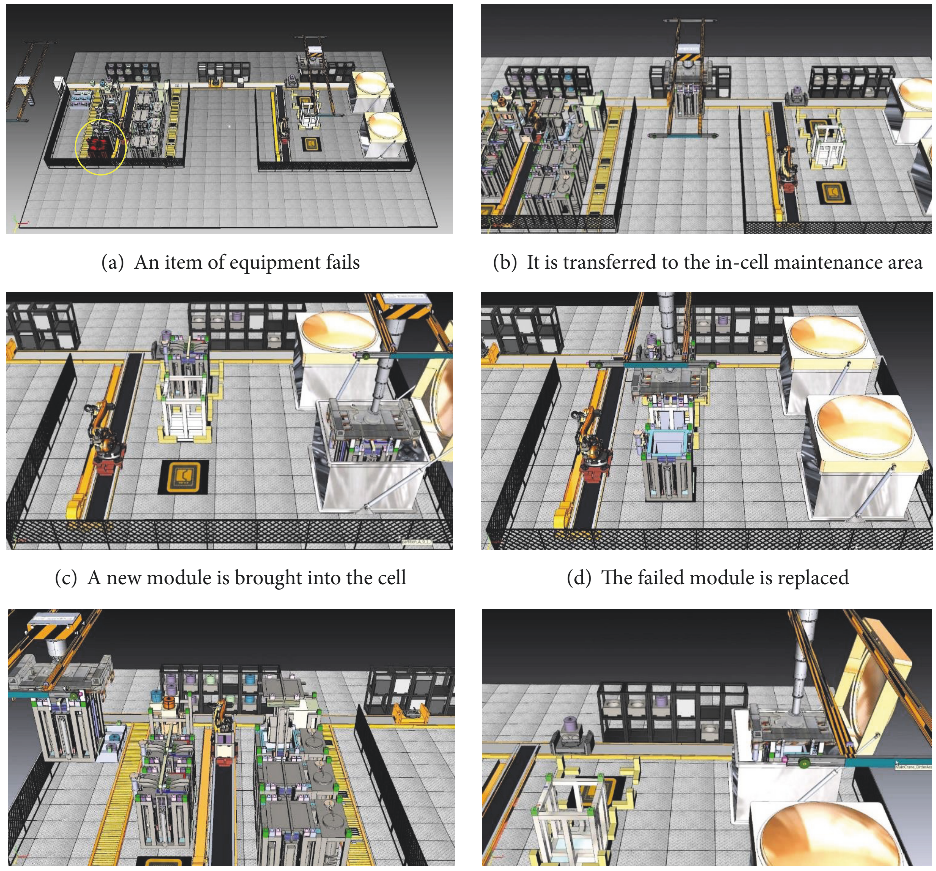
First, when the maintenance operations start, the large-module handling equipment transfers the entire equipment automatically to the in-cell maintenance area (Figure 9(b)). The reason why the entire equipment is ordered to be moved is that the process operations can be interrupted during the maintenance of large modules, and the workspace in the process operation areas is insufficient to replace large modules. In addition, transferring the entire equipment makes it easier to treat the process materials in the vessel during maintenance, and it is also possible to test the equipment before transferring it back to the process operation area.

Afterwards, a new module is brought into the hot cell for replacement (Figure 9(c)), and the vessel is replaced with a new one (Figure 9(d)). In this step, the failed vessel is moved with the cover to a temporary stand, the new vessel is installed on the equipment, and then the cover is transferred back onto the new vessel of the equipment. After this replacement, the repaired equipment is tested and transferred back for reinstallation (Figure 9(e)). The maintenance operations are completed after the failed module is transferred to a decontamination hot cell for further repair or disposal (Figure 9(f)).

As shown, it was verified that the maintenance operations were automatically performed according to the detailed schedules commanded by the PES and the block controller systems in the virtual pyroprocessing hot cell. This concept can also be applied to the replacement automation of other modules.

5. Conclusion

In this paper, a conceptual framework for automating the maintenance of pyroprocess equipment in a hot cell was proposed for the first time. In this framework, maintenance operations can be interpreted as sequential transportation of equipment modules so that the maintenance tasks can be automated by automating the module transfer. For this reason, a conceptual framework for maintenance automation was developed based on a process automation framework. The possibility of the proposed framework was verified by a simulation study of a large module's automated maintenance in a hardware-in-the-loop system with virtual pyroprocessing hot cells. Further studies will be performed for various situations by using the pyroprocess automation framework, including maintenance automation.



(a) An item of equipment fails
(b) It is transferred to the in-cell maintenance area
(c) A new module is brought into the cell
(d) The failed module is replaced
(e) The repaired equipment is transferred back
(f) The failed module is transferred out

Figure 9: Maintenance automation procedure in the case of the reaction vessel replacement.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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