Distance Cooperative Work Support and Work Information Sharing Systems for Multiple Workers in Chemical Plants

(化学プラントにおける遠隔協動作業支援作業情報共有システム)

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Abstracts

Currently, there are many petrochemical foundation products and petrochemical derivatives being both produced and used in chemical plants. These products are indispensable in many industrial fields, such as Japanese plastic product manufacturing, automobile and electronics manufacturing, and rubber product manufacturing, among others. Because chemical plants are part of capital-intensive industries, their automation and labor-saving strategies are advanced, and the involvement of skilled workers is decreasing. Notably, many substances that are handled in chemical plants have potential hazards, such as flammability, explosiveness, toxicity, and corrosiveness. Accidents in chemical plants are caused by hazardous substances, equipment failures, and human factors. According to statistical data, approximately 40% of accidents are due to human factors, including misrecognition, incorrect operation, contact mistakes, etc. Chemical plant workers are generally responsible for their specific work places, while board operators, who work cooperatively with field operators, are in charge of monitoring and remotely controlling equipment, such as valves and pumps, from control rooms. In distance cooperative work, operators often succumb to misrecognition, conduct erroneous operations, make contact mistakes, etc., which are regarded as human factors. Thus, sharing plant information is important for making quick and appropriate decisions.

This study focused on how the proposed system prevents human errors. In this thesis, the proposed system is described in six chapters:

Chapter 1 introduces the current state of and problems with technology concerning the prevention of accidents in the operation of chemical plants as well as disaster prevention at the time of the accident. This chapter then describes both the purpose of this research and the composition of this thesis.

In Chapter 2, a summary of the related study, including experiences regarding work support and information sharing systems in chemical plants, is presented. A method for inheritance and sharing information through the advancement of information technology is also examined.

Chapter 3 considers the work information presentation system, which is intended to prevent human errors via image processing techniques. The operator captures the target equipment using the tablet PC's camera. Template matching, which is an image processing technique, is used to specify the target equipment, such as valves, which are reflected in real-time images. Because different kinds of equipment have the same type of setting in a narrow space, the operator needs to capture the background that is shifted to the photographed image for accurate recognition. The system also uses the background image's features to identify the target equipment. In addition, a method for standardizing and revising the operation procedure manual was prepared, per the concept of 6W2H, to cope with unskilled operators. In the case example, it became possible to identify different types of machinery and equipment. The use of standardized operation manuals also helped reduce erroneous operation by unskilled operators.

Chapter 4 describes the instructional information system using image recognition (IR) and augmented reality (AR) technologies for the prevention of operator errors. With only template matching technology, it is difficult to distinguish different types of machine equipment with 100% accuracy. Therefore, this study proposes a method for improving the discrimination accuracy of machine equipment by combining IR and AR technologies. Furthermore, it presents a function that can record the field operator's work history in the database and an information sharing function that provides work information via the server. The case examples indicate that it is possible to prevent misjudgment of different types of machine equipment. Notably, the operation history is automatically stored in the system's database. The accumulated work information is important for safety management and can be shared and utilized by all workers. With the proposed system, the field operator can recognize work target equipment via IR/AR technology, and the system displays the correct work procedures to site workers. The field operator can accurately check the work target equipment and work procedures onsite with this system as well, which can be beneficial for securing the safety of onsite workers as well as for preventing erroneous operation and judgment.

Chapter 5 explains an information sharing system that aims to enhance the safety of distance cooperative work. This system has functions to support both board operators and field operators at work sites. The system also allows for the sharing of real-time on-site images, along with work information that is necessary for operation. In addition to instruction information by a human voice from the control room to the site worker, correct work information is transmitted by a simple text display. Field operators can utilize two-way communication to obtain direction from the control room with the Yes-No button. In the chemical plant, a dynamic simulator has been installed that predicts the machine's behavior by inputting the present condition of the operator at the site and the operation amount of the facility. Therefore, in addition to facility operation procedures, information on the equipment's state is grasped in the control room, and information on behaviors that are predicted by the simulator is presented to the field operators. The system refers sensor data and displays plant information to the field operator on his/her tablet PC. The case example showed that the onsite operator can share the above information with board operators and thus carry out cooperative work both safely and securely.

To conclude this thesis, Chapter 6 summarizes the presented study on distance cooperative work support and work information sharing systems for multiple workers in chemical plants and states that the results are expected to prevent accidents that are caused by human factors in chemical plants.

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Chapter 1 Introduction

1.1 Current issues in safety management of large-scale chemical plants

Preventing accidents in chemical plants is crucial to protecting the safety of employees and local residents. However, the number of accidents that occurred from 1989 to 2014 has been increasing, and several accidents at large industrial facilities have occurred continuously. Figure 1.1 below is an outline of the accident [1] that occurred at a specific office within the special disaster prevention area such as the petroleum industrial complex of the Ministry of Internal Affairs and Communications in the year of the Heisei 28 (2016), announced May 30, Heisei 29 (2017).

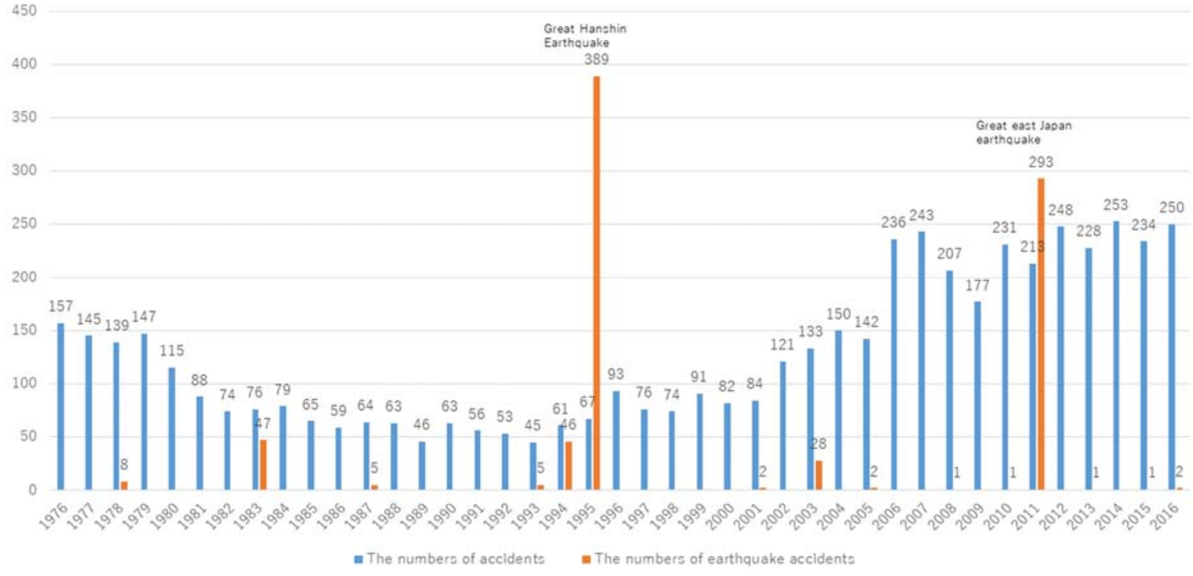

Figure 1.1 Accident situation of petrochemical industrial complex

According to a recent report by the Japanese government, about 40% of accidents in the chemical industrial complex are caused by human factors, including misjudgment, misoperation, recognitions and confirmation error. Detailed information on the accident trend in chemical plants was published in the report “Liaison Committee for Municipalities and Agencies Reviewing Measures for the Prevention of Industrial Accidents at Petrochemical

Complexes, etc.” The report was compiled via a Joint Press Release with the Fire and Disaster Management Agency and the Ministry of Health, Labor, and Welfare of Japan (2015) [1]. In FY2014, there were 253 accidents reported by 697 establishments in special disaster prevention areas such as petrochemical industrial complexes, totaling 24 cases more than the previous year. Of the total number of cases, 98 (39.0%) were due to human factors,140 (55.3%) were due to physical factors (e.g., corrosion, equipment failure), and 15 (6.0%) were due to disasters such as earthquakes, arson, and others. It can be seen from Figure 1.2 that the ratio of accident occurrence factors has not changed substantially during the five years from 2012 to 2016.

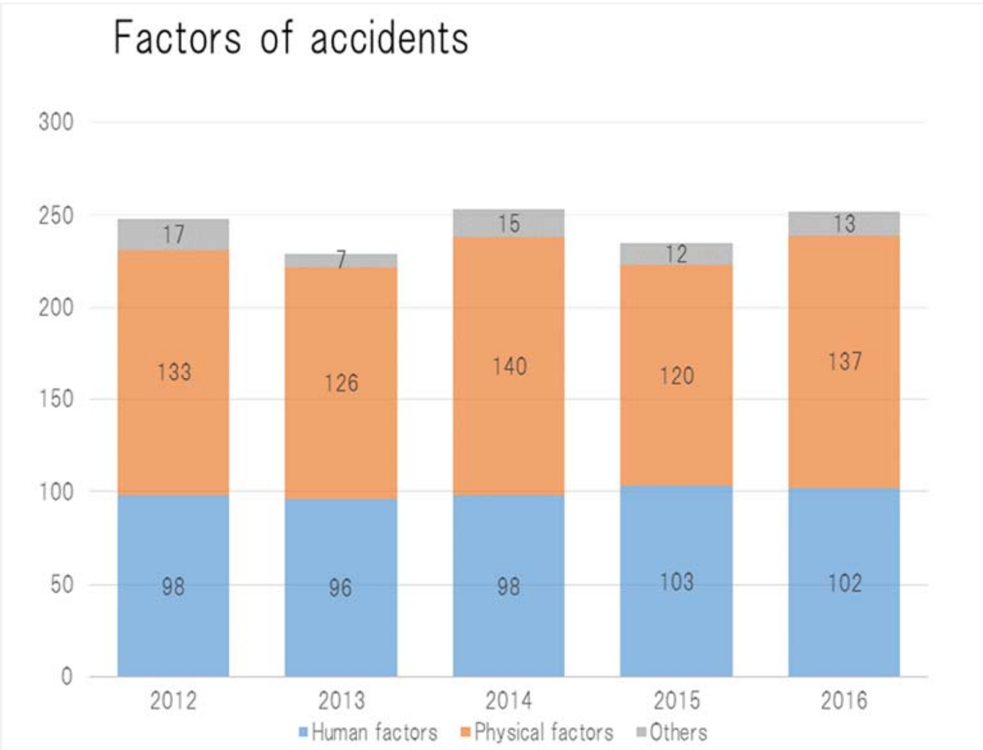

Figure 1.2 Factors of accidents of petrochemical industrial complex

Nowadays industrial technology has changed, becoming highly diversified and complicated; especially in an emergency, plant operators are having more trouble grasping the overall situation. As causes of industrial accidents, there are many types of human errors, such as cognition/confirmation mistakes, misoperation, and misjudgment by employees. In terms of the number of accidents in 2014, 58 of the cases (23.0%) caused by human factors were due to misoperation and insufficient operation confirmation.

In addition, industrial complexes dotted in various parts of Japan are one of Japan's leading production bases such as energy, steel, petrochemical products, automobiles, etc. In the unlikely event that large-scale manufacturing facilities suffer accidents/troubles and natural disasters, their operation will stop by the emergency shut down. The damage amount is enormous and have a great influence on the residents and domestic enterprises. At the same time, due to changes in the social structure, problems of retirement of a large number of mandatory retirements at the manufacturing site and technical inheritance due to a decrease in the labor force population have been pointed out. Under these circumstances, it is necessary to review the roles played by people in production activities [2].

1.1.1 Features of production activities in the process industry

Production activities in petrochemical plants are significantly different from assembly and processing industries where workers handle products directly. From raw materials to final products, things (substances) flow through equipment such as piping, towers and the like in chemical plant. Therefore, during the manufacturing process in chemical plant, it is impossible for the on-site workers to confirm directly the state of things and the manner of change. The operator's work in the process industry is lower in visibility than the assembly and processing industries, and it is not directly controlling the chemical/physical phenomenon during the manufacturing process. But rather the operator is managing the information (process data) obtained indirectly through the sensor. For this reason, an operator who performs a monitoring (board) work in the control room works based on knowledge obtained from a large amount of sensor information during the manufacturing process and their past experience due to lower visibility plant behavior. They estimate the state of the fluid inside and perform monitoring, judgment and operation as a daily task. In the event of a site operation that cannot be controlled in the control room, the operator interacts with the site workers and performs necessary work. In this case, the operator cannot directly confirm the situation at the site from the control room. Production activity in chemical plants has such lack of dual visual information. Production activity in chemical plants has such lack of dual visual information. One is real plant behavior and the other is real-time onsite situation.

As described above, one of the major characteristics of the process industry is inevitably intervening information processing and judgment by a human being in the manufacturing process. Thus, operators/onsite workers in chemical plant specific to the process industry are required to make quick decisions based on a very higher extensive knowledge and experience, and it can be said that they are important elements of the production system.

1.1.2 Social meaning of safety management of petrochemical plants

The process industry is a highly energy-consuming industry characterized by a large number of production processes under handling of dangerous substances and under heavy load conditions, and high safety is required. The following points are key to strengthening competitiveness in the process industry.

(1) Management of manufacturing processes is complicated, expensive facilities cannot easily be changed and reconstructed.

(2) A large amount of energy and days are necessary at the time of starting and stopping the plant, resulting in a large burden on safety, quality and cost.

The petrochemical industry is the core industry of our country. It is essential to consider current facilities and human problems and to improve production activities.

However, the production process of petrochemical plants is very complicated. It is extremely difficult to introduce simple and clear rules that assemble to the management of petrochemical plants and automatically optimize processing plants. In my opinion we should make full use of human resource for safe driving of petrochemical plants.

1.1.3 Recent accidents and their factors

The Ministry of Economy, Trade and Industry's Industrial Structure Council preservation subcommittee 6th Report 1 "Recent Accident Status" was published in Heisei 28 (2016) [3]. Among them, examples of serious accidents in large-scale plants handling high-pressure gas etc. have been reported. In this material, as a tendency of accident cause related to the High Pressure Gas Safety Law described following, accidents are caused by "corrosion management failure" and "inspection management failure" on the equipment side problems, and those caused from "erroneous operation / misjudgment" by human factors. Recent serious accidents are as follows.

1. Explosion death accident at vinyl chloride monomer facility

Figure 1.3 Vinyl chloride monomer facility

At 3:24 pm on November 13, 2011, an explosion accident occurred during the operation to extract vinyl chloride monomer facility at Yamaguchi Prefecture, Shunan City in Figure 1.3. As hydrogen chloride gas leaked due to the fire, residents were called indoor waiting. Due to the explosion accident, wastewater containing ethane dichloride, which is 155 times the regulated value, leaked into the sea. In addition, one male employee died in this accident. The prospect that the 10 billion yen unit will be needed for the rebuilding of facilities burned in the accident has been clarified.

2. Explosive death accident at resorcinol production facility

Figure 1.4 Resorcinol production facility

Figure 1.4 shows plant explosion accident occurred in Waki Town, Yamaguchi Prefecture on April 22, 2012. A resorcinol production plant used for raw materials of tire adhesives exploded and a fire occurred. Equipment and piping adjacent had fire spread over, and after the tank of the same plant exploded again around 8:05 am, it was extinguished at 5:15 p.m. the same day. One employee on the premises died, 22 people including local residents were injured, causing 484 houses in neighboring areas to be damaged.

3. Explosion death accident at acrylic acid manufacturing facility

Figure 1.5 Acrylic acid manufacturing facility

On September 29, 2012, a tank of chemicals (acrylic acid) exploded at the Himeji, Hyogo prefecture, and this started as a large fire occurred. As a result, one firefighter of Himeji City fire department died, 36 employees of the same manufacturing factory and Hyogo prefectural police officials also suffered serious injuries such as burns. In response to this accident the product production facility of the Himeji manufacturing facility was ordered to stop using in Figure 1.5.

4. Explosive death accident at polycrystalline silicon manufacturing facility

Figure 1.6 polycrystalline silicon manufacturing facility

An accident occurred in cleaning the heat exchanger of the hydrogen refining equipment which cools the silicon raw material in the first plant which manufactures high purity polycrystalline silicon in Yokkaichi City, Mie Prefecture on January 9, 2014. The heat exchanger is a tubular type with a diameter of about 1 meter and a length of about 5 meters, and removed from the equipment on 27 November 2013 to remove solid burnable substances adhering to the inside, It was placed in an outdoor pickling place. The five people who were hit by this explosion died, 13 people suffered serious injuries. Figure 1.6 shows the site of polycrystalline silicon manufacturing facility

5. Coke fire accident at steelworks

In 2014, Wednesday, September 3, coke plant No. 1 coke oven coal tower in Aichi Prefecture, a fire accident occurred, 15 persons injured suffered from human injury did. The propagation of the flame ranged from the No. 1 relay tower to the gallery headed for No. 3 coke oven to a large extent. Part of the roof of No. 1 relay tower and the wall of the gallery were partially damaged due to hot air and wind pressure generated by the propagation of the flame. Figure 1.7 shows the accident situation.

Figure 1.7 Coke fire accident at steelworks

Before a severe accident actually occurs, there are indirect factors such as operation and facility management, safety / disaster prevention activities, organization management, etc.. In the background as well as the direct cause, and in considering recurrence prevention measures, it is necessary to clarify the causal relation between them. According to the data, the following items are considered as common problems for serious accidents [4~8].

① Insufficient risk assessment
② Inheritances of expert knowledge/skills and human resources development
③ Problems in sharing accident information in the past experiences

A recent serious accident was caused by an artificial mistake and while accidents have occurred repeatedly from the past, the lessons of past accidents are not shared, moreover, it is not utilized. Chemical plant operators are required to make quick decisions to prevent the expansion of an accident. We consider that there are many human factors, such as misjudgement or miscommunication. And also accidents often occur in non-steady-state operation. At the time of an accident or disaster such as a non-stationary, emergency response operation is required. To convey accurately indication information of work in chemical plant, we need safety systems to support operators/workers to follow correct operating procedures without human error.

1.2 Basic concepts for Safe society

The concept of "safety" is generally said to be "there is no danger" or "there is no danger of being harmed or damaged or damaged". Is there a situation where there is 100% safe in reality? No matter how careful we are, we get injured by small things and the possibility of encountering a traffic accident is not zero. People are living in a state of daily uncertainty and understand "safety" as "the state or situation as a result of thinking that the possibility of causing a disadvantage of harm or damage is extremely low". "Risk" is expressed by a combination of two factors, the probability of occurrence of harm and the degree of harm (magnitude). According to ISO/IEC Guide 51, it is defined as follows. Risk: Combination of probability of occurrence of harm and degree of harm. Similarly, the definition of "safety" is as follows. Safety: There is no unacceptable risk. ISO/IEC Guide 51 is a guideline for introducing safety regulations in the standard, the official name is "Safety aspects; Guidelines for their inclusion in standards". This guideline was issued in 1990 and also adopted as a "guideline for introduction to JIS Z 8051: 2004 Safety Aspect - Standard" in Japan in 2004 as well. Although these guidelines are excluded from speculative fields such as insurance and investment, they are used for creating safety standards in a wide range of fields such as medical care, chemistry, machinery, and electricity. In the international safety standards, safety is defined via risks and risk assessment is required as a methodology for risk reduction.

Meanwhile, in Japan, the idea of absolute safety was dominant. In other words, despite the requirement that the risk be zero, even in the presence of potential hazards, in many cases, we have tried to avoid it by human experience and wisdom and to ensure safety. However, it can be said that this way of thinking has not clearly defined the logical thinking about risk recognition and risk mitigation. In order to solve such problems and ensure the safety of people and facilities, it is necessary to convert consciousness from risk-based risk assessment to risk reduction based on conventional absolute safety concept. In other words, safety can be achieved by reducing the potential risk to the plant [9,10,11].

1.3 The purpose of this study

As mentioned in the previous section, chemical plants have potential hazards and therefore safety measures need to be established. Safety management of chemical plants has its own risk. The operators cannot actually confirm the production process from raw material through products through the piping or tank, e.g.. In the usual case chemical plant workers have responsible on their specific work place: equipment operations such as valves and pumps are cooperatively performed by onsite operators and control room operators who are in charge of monitoring/remote control from the control room. The control room and the site exist separately from each other, and it is impossible to actually confirm on site work from the control room. Moreover, it is not possible to directly confirm the plant information of the DCS operation board at the site. The operator repeatedly contacts the control room and the work site until the task of stabilizing the plant is completed. Thus, sharing plant information is important to make quick decisions to control equipment. In addition, misoperation tends to occur in petrochemical plants because they contain numerous machineries with the same form but with different contents; these differ even though the shape and model of the valves and pipes may be the same. Based on these facts, this study focused how the system prevents human error like miscommunication or misunderstanding. In addition, by deepening interest and understanding about facilities, it can be made that the technology for large-scale plant safety management is further improved. I examined the relationship between people and machines in the progress of field Work [6,11]. There are cases where accidents caused by equipment failure in chemical plants have advanced to serious accidents due to incorrect response by subsequent operators [12,13,14]. Regarding such unsteady/emergency response operation, it is necessary to carry out education and training from around the day. Enhancement of countermeasures at disasters and severe accidents in manufacturing facilities and dangerous materials handling facilities is required from both human and facility side. In a chemical plant, it is an important factor for human behavior to keep safety production activities. In distance cooperative work, operators often succumb to misrecognition, conduct erroneous operations, make contact mistakes, etc., which are regarded as human factors. Thus, sharing plant information is important for making quick and appropriate decisions.

1.4 Thesis statement and overview

This study focused on how the proposed system prevents human errors. In this thesis, the proposed system is described in six chapters:

Chapter 1 introduces the current state of and problems with technology concerning the prevention of accidents in the operation of chemical plants as well as disaster prevention at the time of the accident. This chapter then describes both the purpose of this research and the composition of this thesis.

In Chapter 2, a summary of the related study, including experiences regarding work support and information sharing systems in chemical plants, is presented. A method for inheritance and sharing information through the advancement of information technology is also examined. This thesis is a summary of the study results so far and consists of 6 chapters in all.

Chapter 3 considers the work information presentation system, which is intended to prevent human errors via image processing techniques. The operator captures the target equipment using the tablet PC's camera. Template matching, which is an image processing technique, is used to specify the target equipment, such as valves, which are reflected in real-time images. Because different kinds of equipment have the same type of setting in a narrow space, the operator needs to capture the background that is shifted to the photographed image for accurate recognition. The system also uses the background image's features to identify the target equipment. In addition, a method for standardizing and revising the operation procedure manual was prepared, per the concept of 6W2H, to cope with unskilled operators. In the case example, it became possible to identify different types of machinery and equipment. The use of standardized operation manuals also helped reduce erroneous operation by unskilled operators.

Chapter 4 describes the instructional information system using image recognition (IR) and augmented reality (AR) technologies for the prevention of operator errors. With only template matching technology, it is difficult to distinguish different types of machine equipment with 100% accuracy. Therefore, this study proposes a method for improving the discrimination accuracy of machine equipment by combining IR and AR technologies. Furthermore, it presents a function that can record the field operator’s work history in the database and an information sharing function that provides work information via the server. The case examples indicate that it is possible to prevent misjudgment of different types of machine equipment. Notably, the operation history is automatically stored in the system’s database. The accumulated work information is important for safety management and can be shared and utilized by all workers. With the proposed system, the field operator can recognize work target equipment via IR/AR technology, and the system displays the correct work procedures to site workers. The field operator can accurately check the work target equipment and work procedures onsite with this system as well, which can be beneficial for securing the safety of onsite workers as well as for preventing erroneous operation and judgment.

Chapter 5 explains an information sharing system that aims to enhance the safety of distance cooperative work. This system has functions to support both board operators and field operators at work sites. The system also allows for the sharing of real-time on-site images, along with work information that is necessary for operation. In addition to instruction information by a human voice from the control room to the site worker, correct work information is transmitted by a simple text display. Field operators can utilize two-way communication to obtain direction from the control room with the Yes-No button. In the chemical plant, a dynamic simulator has been installed that predicts the machine’s behavior by inputting the present condition of the operator at the site and the operation amount of the facility. Therefore, in addition to facility operation procedures, information on the equipment’s state is grasped in the control room, and information on behaviors that are predicted by the simulator is presented to the field operators. The system refers sensor data and displays plant information to the field operator on his/her tablet PC. The case example showed that the onsite operator can share the above information with board operators and thus carry out cooperative work both safely and securely.

To conclude this thesis, Chapter 6 summarizes the presented study on distance cooperative work support and work information sharing systems for multiple workers in chemical plants and states that the results are expected to prevent accidents that are caused by human factors in chemical plants.

Chapter 2 Related Study and Experience

2.1 Study on safety support of chemical plant

In order to improve safety in a process plant dealing with dangerous substances, it is necessary to clarify the hazards hidden in the plant and to carry out safety assessment to decide appropriate countermeasures. Many studies on hazard analysis methods including Hazard and Operability Study (HAZOP) analysis method have already been reported to ensure plant and process safety and reliability[16~22]. The main methods developed for the risk analysis of chemical plants are as followings, HAZOP (Hazard and Operability Study), FTA(Fault Tree Analysis), ETA (Event Tree Analysis), FMEA (Failure Mode, Effects Analysis). HAZOP is a qualitative risk assessment method, which is used in a wide range of fields today [23, 24]. Although these analytical methods have been qualitatively analyzed by humans, research involving computer analysis has expanded since it takes a lot of time and cost [25,26,27]. By introducing computer technology, it became possible to conduct safety assessment without analyzing results depending on the analyzer [28,29]. Venkatasubramanian [30,31], Chung [32,33], and many other researchers have been working on realizing HAZOP automatic analysis system. In 2000, H. Graf proposed a new analytical method for computer-based safety design. This research forms a qualitative plant model in the state chart as a basic element of identification of process hazards by simulation and analysis. Simulation was performed by modeling the procedure of HAZOP [34]. Thus, by introducing computer technology to the conventional risk analysis method, new research such as combining analytical methods and incorporating a quantitative perspective into qualitative analysis has come to be carried out. Netta Liin Rossing [35] modeled a chemical plant that is to be analyzed using a model of the function of process plant as a multilevel flow model (MFM) in 2010, the flow of matter, energy and information. Safety support for chemical plants has evolved from the automation of hazard analysis methods[36,37]. Research on plant operation support is currently underway due to advances in computer technology.

2.2 Study on safety support of operators in chemical plant

In the previous section, it is described the study on facility safety of chemical plants [38～49]. Due to advances in information technology, the operation of plants has been advanced and DCS (distributed control system) has been introduced for plant equipment control. Safety management centered on conventional facilities has been extended to research that improves the safety of plants by supporting operators [50,51,52]. It is reviewed here image recognition technology, VR (Virtual reality), AR (Augmented reality) technology, work information system by advanced computer technology such as dynamic simulator, work support research [51,53,54,55]. Computer technologies to complement human ability are developed in safety support research [56,57,58]. Recently, with the evolution of hardware anyone can easily change the information they want anywhere.

2.2.1 Technological inheritance of industrial field

Inheritance of technology at the industrial site has many problems due to changes in social structure [6,11,16,53]. The declining birthrate and aging population are progressing in Japan due to changes social issue. The working environment has also become more sophisticated, advancing to labor saving, and it has changed drastically [16]. At the industrial site, the core knowledge and expertise to be handed over to the next generation is not clear. It is urged to deal with urgent issues such as preparing the succession environment throughout the organization. Industrial fields should consider measures that impede technology succession and take countermeasures. Knowledge management is necessary for efficient technology inheritance. Standardization of work and education/training are indispensable elements for inheriting technology at site work.

2.2.2 Computer technology for work support

Research to support work inheritance using computer technology has been reported recently [59~68]. Technologies that complement human senses such as image recognition, virtual reality, and augmented reality are utilized for work support. "Image recognition" is a kind of pattern recognition technology, and is a method of recognizing and detecting objects and features such as characters and faces from images and moving images [69]. Virtual reality technology (virtual reality) is also referred to as artificial reality, combines computer graphics and sound effects, artificially creates reality, reproduces accidents and anomalies that cannot be realized in mock-ups or actual plants. Then we can let it experience [70,71]. Augmented Reality (AR) is a technology for adding information to the real environment [72] and displaying it [73]. In addition, it has a recognition function by voice and video, and information which is not visible to the operator can be visualized [74,75]. With the evolution of computer equipment in recent years such technology has become easy to use anyone [76].

Information terminals that can be carried on are not yet widely used in petrochemical plants due to not have explosion proof function of equipment. Install of information devices for work support in petrochemical plants is currently under investigation and attention is being paid to future application methods [77,78].

2.2.3 Study on work support system for operators

Since rationalization of large-scale plants has advanced rapidly, research to support operators has been conducted. Various studies have been reported from about 1990 along with progress of computer technology. There are many researches that can be used for educating workers to make use of the features of technology. Chen Xi [50] developed a system that uses 3D space to train while Avatar walks through with third person viewpoint. This is a system where the avatar trains while walking through the 3D space using the third person viewpoint. With respect to abnormalities occurring within the VR environment, it is possible to operate the equipment and learn the equipment operation and procedure at the time of the abnormality. However, the content that can be trained is only the scenario created by the development team, and its content is limited. There is a problem that the user side cannot correct or change later. Stephan E [51] prepared a lot of real plant photos, created a VR space by connecting these photos, and created a walkthrough VR system that learned operating procedures and principles in that VR space. Click on the target device from the P & ID diagram and display the operation procedure of the selected device in a flow chart. And the user can learn the operation by operating in the VR space according to the procedure. However, because there is no image of the accident against the wrong operation, it lacks the sense of reality. It is impossible to experience accidents/abnormal experiences when the operation fails, and work done by multiple people is not considered. Yumoto et. al [52] proposed an operation training system applying a plant simulator called "Omega Land OTS Enterprise". In this system, dynamic behavior of a plant is simulated with a dynamic simulator, and understanding and manipulation of phenomena can be learned using an instrumentation device or computational simulation. In addition, a DCS screen for the operator and a field operation screen for the field man are prepared. In that environment, multiple operators learn operations similar to real systems, as well as cooperation as a team, equipment trouble, and response to abnormal situations of plants. However, in this system, there is a problem that it is difficult to visually recognize by numerical or character series of numbers and letters. Also, since it is a two-dimensional graphic, it is considered difficult for a trainee on field side to have strong image of the actual site. Yamamoto et al [53] proposed a system that trains in the VR environment by quantifying the VR environment by linking the VR environment and the plant simulator. This system creates a scenario describing the behavior of the plant beforehand and changes the VR environment according to that condition. Therefore, if it is outside the intention of the scenario creator, it cannot be reflected in the VR environment. Thus, this system only covers the heating furnace and a few valves around it, and the behavior of the plant is represented in one scenario. However, when the scope of application expands and the degree of freedom of the trainee increases, the branching of the scenario becomes complicated, making it difficult to create a scenario. Research on a rigorous driving training simulator based on integration of 3D technology by US IPS (Invensys Process Systems) Co., Ltd. [54], Hayashi [55] is conducted as a research for a training system in a plant using VR technology by companies. By using detailed 3D models and dynamic simulators, it is possible to safely perform driving training of abnormal conditions that cannot be normally experienced, such as in a non-steady state. However, since the process values of the 3D model and the dynamic simulator are always linked, the accurate time change is reflected in the virtual space. As a result, a trainee waiting for a response to an operation occurs, which may result in a long training time and reduced concentration ability of the trainee. Also, because the scenario created by the development team is trained by a simulator, there is a problem that the range of selection of the scenario is narrowed and the user side cannot correct or change later. Research and the like by Ishii et al., Kyoto et al. [56, 57] are conducted as research on the development of a training system for educating abnormality diagnosis of a nuclear power plan. By linking with a human model simulator that performs abnormality diagnosis of the plant, it is possible to observe how the avatar performs plant abnormality diagnosis in the virtual space. Younghee Lee [58] showed a system to improve the safety of work by training the operation method of the equipment in the refueling area of the automobile using hydrogen as the fuel by using VR. It is aimed at educating hydrogen fuel refueling operation which safety is important for handling. Train by moving freely on refueling on VR space using mouse and keyboard. The scenario is based on an actual hydrogen accident and is a scenario with 50 final events using 20 accident cases. Although scenarios are created based on accidents caused by hydrogen, responses after the accident must be done independently, and work by multiple people is not taken into consideration. Michal Ponder et.al. [59] and others have proposed a training system for two people using decision making by trainers and supervisors. In this research time limit is set for decision making. In the study of Manca et.al. [60], it is possible to reproduce a qualitative plant by integrating it with a dynamic simulator using VR technology. Accurate operation procedures and equipment information are indispensable for securing the safety of site workers. With the progress of computer technology, the information display function expanded. Augmented Reality (AR) is a technology for adding information to the real environment and displaying it. In addition, it has a recognition function by voice and video, and information which is not visible to the operator can be visualized. AR technology has been studied since the 1960 's [82]. Whereas VR (virtual reality) experiences artificially created environments in virtual space, AR objects and environments are expanded and added to the real world by computers. VR is suitable for reality experience, reproduction suitable for dangerous work and test environment, and it is effective for work training for experiencing training, in virtual reality. AR is excellent as a technology to support real work actually doing. The system developed by L. B. Rosenberg of the Armstrong Air Force Research Institute in 1992 is the earliest functioning AR system [61,62], Research and development was advanced in the fields of medicine, video, game development, etc. in the 2000s [74,74]. In Japan as well, mobile devices become popular, AR technology has become commonly known, and now it is also being used in business scenes [65, 66]. Ishii and colleagues [67] are examining what features and problems exist by referring to disconnection sites and expressing images after demolition with augmented reality during the decommissioning of nuclear power plants. It is useful to use augmented reality in reference and recording of cut points and it is possible to use it as a preliminary education for beginners and a foreign appeal [65,67]. Even for research on "next-generation HMS for advanced operation of nuclear power plants" started in FY 2001, AR technology is also applied to driving support and work support for field workers in HMS (Human Machine Interface System) It has been reported that it can be utilized in practice [79]. Sato et al. [80] developed an information processing system aiming at the needs of on-site work support as information addition technology with computer focusing as a supplementary defect in the efficiency of maintenance and conservation activities in nuclear power plants. In this research, the effectiveness was demonstrated by presenting information to the site of maintenance work using mobile information terminal as a mobile agent. In the safe operating and support system of chemical plants, there is a wearable chemical plant monitoring system utilizing the six senses of Naef et.al. [74] "Oil plant maintenance and inspection work support system" developed by Toyo Engineering Corporation [81] carries out real-time information sharing and work support in the work site and the central control room by the maintenance inspection work management system and the work information database. AR technology can present necessary information to the real environment at real time. It can efficiently show work procedures to young workers unfamiliar with chemical plants and how to handle equipment, so it can be used for education and training.

2.3 Work instruction and information sharing in chemical plant

Operators in petrochemical plants have problems with many hazardous substances and facility management. Large-scale plant is controlled by distributed control system. Since the work targets are located separately, the operators are driving based on the information of the DCS, which is actually happening real time. Field work cannot be actually confirmed from the central control room and accurate plant information cannot be confirmed on site. Instruction of work information on work relies on communication information by voice. In an operation site of a chemical plant, it is an environment in which mistakes and misrecognition are likely to occur. There are cases where accidents have expanded due to human factors, and measures are needed to ensure on-site work. Accidents tend to occur in unsteady work and single person work [83, 84]. Although the information necessary for work is shown in the work procedure manual, it is difficult to reference on the onsite because there are many expressions by the document. This study is considered using a mobile information device for confirming work procedures and sharing information and carrying out effective work support. The systems are proposed that connects invisible parts of existing plant work by computer technology and performs safe collaborative work. In this research, it is emphasized knowledge and experiences that tend to belong to people such as skills and know-how, standardize and generalize. It is essential that this make the work procedure manual a technology level that everyone can utilize safety. The proposed system is incorporate the elements of knowledge management. Through this study it is described the mechanism which realizes cooperate work by information sharing for realizing safe onsite work.

Chapter 3 Instructional Information System using Image Recognition Technology

3.1 Introduction

Preventing accidents in petrochemical plants is important for protecting the safety of not only employees but also the inhabitants in the surrounding area. Detailed information on accidents in petrochemical plants is published on the joint website of the FDMA, MHLW, and METI [1]. The number of accidents has been on the rise since 1989. In 2014, the 697 plants in the special area of disaster prevention for petrochemical complexes reported 253 accidents, numbering to 24 more than the previous year. Of that number, 17 caused the loss of human life, and 81 individuals died or got injured. The causes of the accidents were traced to human error in 98 cases, physical issues in 140 cases, and disasters such as earthquakes, arson, and others in 15 cases. Human error incudes misjudgment, mistakes in operations, and awareness/confirmation failures. In this paper, incorrect judgments made as a result of insufficient knowledge or experience are referred to as "misjudgments." Incorrect operating procedures, operating details and operating targets are referred to as "misoperations." Lack of knowledge of operating targets and procedures and lack of understanding of and failure to carry out operation checks are categorized as "awareness/confirmation failures."

Human errors have various causes. The following on-site operation is assumed to clarify the scope of application of the technique proposed in this paper. The on-site operator (referred to as the "fieldman" hereafter) and the boardman, who conducts observation and remote operation from the control room, jointly operate machinery such as valves and pumps. Communication between the boardman and the fieldman is conducted mainly through sounds, such as paging. Misjudgments and awareness/confirmation failures due to misunderstandings and assumptions tend to occur when communicating through sounds. In addition, misoperation tends to occur in petrochemical plants because they contain numerous machineries with the same form but with different contents; these differ even though the shape and model of the valves and pipes may be the same.

Operation-support systems that use augmented reality technology as a means of preventing accidents due to human error are being developed [94]. It is possible to confirm operating targets from among various types of machinery using augmented reality technology. However, using supporting machinery, such as AR markers and IC tags, is necessary. In petrochemical plants, there are many areas where supporting machinery cannot be installed due to restrictions of temperature, space, or other factors. Image-recognition technology would be a means of confirming operating targets without using assistance machinery [95]. Conventional image recognition techniques' main purpose is to extract a specific target object from among a group of images. Therefore, it is necessary to devise a way of confirming the operating target among different machines with the same form.

Operating-procedure manuals are widely used as part of a realistic measure to prevent accidents due to human error [91]. Operating-procedure manuals describe operational procedures that produce the same results regardless whether the performer is an expert or a novice, as long as the procedure is followed. As such manuals are generally in paper format, glossing over the operating procedure or misidentifying the operating target are potential risks. Furthermore, to control the complexity of the operating-procedure manual, detailed operating information is often not stated (e.g., operation timing, operation duration, operation method, and number of operators). Thus, it is difficult to prevent accidents due to human error simply by copying existing paper operating procedures and incorporating them into information terminals.

Therefore, in this paper, operational procedures stated on paper are reviewed from the perspective of preventing accidents due to human error, and a technique is proposed that can be standardized through inclusion in disaster prevention information terminals. Then, an image recognition technique to confirm operating targets without using special assistance machinery, such as AR markers, is proposed. Operating targets are confirmed based on the background of the installation area and the positional relationship with other machinery. The instructional information system for chemical plant operation has been developed with the aim of preventing human error accidents by incorporating these two methods into information terminals.

3.2 Proposed method

Here, we describe an image recognition method to confirm operating targets and standardize operating procedure manuals.

3.2.1 Operating procedure manual standardization

The content of the operating-procedure manual distributed in paper form is reproduced implicitly and reconstructed to include unstated information. The operation contents are organized based on the 6W2H approach, which supplements the 5W1H approach, standing instead for the eight questions “Who,” “When,” “Where,” “What,” “Why,” “How,” “Whom,” and “How many.” In the case that the duration of operation is also required, 6W3H is used, which adds the consideration “How long.”

To prevent the mixed display of the operational content for the fieldman and the boardman, the operational content is divided according to the role of the operator. The communication/instruction procedures for fieldman only and boardman only are clarified by adding the item “Whom,” which prevents confirmation failures and operational mistakes.

The reorganized operating-procedure manual displays the order of operations using a spreadsheet. Figure 3.1 shows an example of the operating procedure manual, in the form of an operating procedure for indirect desulfurization equipment malfunction countermeasures. The operation is performed in the order of E (00) to E (70). In the Operation E (00) column, the status before the operation is given.

	E(00)		E(10)		E(20)		E(30)
When		When	LC401 Alarm occurrence	When	LC401 Alarm occurrence	When	LC401 Alarm occurrence
Who		Who	Board operator	Who	Field operator	Who	Field operator
whom		whom	Field operator	whom		whom	
where	Feedstock supply	where	Control room	where	Circulation line	where	Circulation line
Why		Why	Prevent to heat the empty device	Why	Prevent to heat the empty device	Why	Prevent to heat the empty device
What	VGO	What	Change circulation system	What	HV811	What	HV813
How	Stop	How	Indication	How	Open	How	Close
How many		How many	LCV401 full open	How many	Full open	How many	Full open
	E(40)		E(50)		E(60)		E(70)
When	Confirmed circulation system	When	After confirmed circulation system	When	Temperature change of furnace	When	Temperature change of furnace
Who	Field operator	Who	Field operator	Who	Board operator	Who	Board operator
whom	Board operator	whom	Board operator	whom		whom	
where	Circulation line	where	Around the distillation tower	where	Control room	where	Control room
Why	Stabilize plant condition	Why	Stabilize plant condition	Why	Control temperature	Why	Reaction stop
What	HV811	What	Status check	What	FC406	What	TC409
How	Adjust valve condition	How	Report to control room	How	Control discharge	How	Lower temperature
How many	D-401レベル確保	How many		How many	120kl/h	How many	250℃

Figure 3.1 Reconstruction of the operating procedure manual based on 6W2H

E (10) in the following operation states that the boardman (Who), having understood that LCV401 is fully open (How many), at the sound of the low alarm for LC401 (When) in the control room (Where) will provide instructions (How) to the fieldman (Whom) to switch the circulation system over (What) to prevent no-water burning (Why). Even with the ensuing operations, the operation contents are described using 6W2H. By stating the subject (Who) of each operation, the operation contents displayed to the fieldman and the operation contents displayed to the boardman are separated [53].

Next, we consider including the operating procedure manual in the information terminal to display operating information to the operator in line with the progress of operation. It is necessary to display individual operations and order relationships using signals. The order of operations presumably includes both sequential and non-sequential series.

Individual operations are denoted as events and are given consecutive numbers. Events contain operating information and are displayed to the operator according to the progress of the operation. Prioritization within events is displayed using an arrow. All operations from first to last are displayed using a flowchart, which as a whole is called an operating-procedure model. A single event describes either a boardman or a fieldman as a subject (Who). Information within an event is displayed to the subject. Each event is represented the following:

$$E_{ij} \quad (i = 0, \cdots, n \quad j = 1, \cdots, m_i)$$

In the event "E_{ij}", i shows the serial number of the operation and j shows the conditional branch. When the plant is operating normally and there is conditional branch to the operation, it is represented as E_{i0}. Prioritization within an event is shown the following:

$$A(E_{ij} , E_{i+1j})$$

Prioritization in event E_{ij} and E_{i+1j} is shown in Figure 3.2 [86].

In the case that an operating procedure model includes operations to deal with a plant in abnormal state, a conditional branch is used. Such a conditional branch is obtained by the following:

$$B_i(\mathrm{i} = 0,1,2, \cdots, NB)$$

$A(E_{ij} , B_i)$ shows the prior relationship between the conditional branch and the upstream event. The prior relationship between the conditional branch and the upstream event is displayed as $A(B_i , E_{i+1j})$, $A(B_i , E_{i+1j+1})$. Figure 3.3 shows an example of a conditional branch [86].

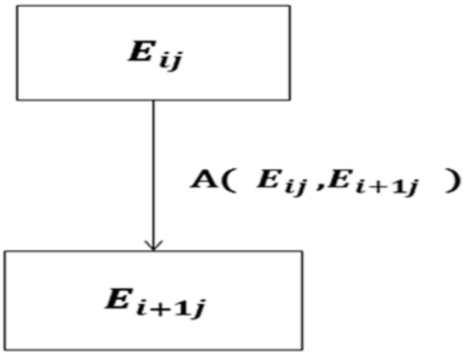

Figure 3.2 Prior relationship between events

The operating procedure manual reorganized to use 6W2H is given in the operating-procedure models in Figures 3.2 and 3.3. Thereby, the operating-procedure model is incorporated into the information terminal, and the operating information can be displayed to the boardman and the fieldman according to the progress of operations.

3.2.2 Confirmation of operating target

To prevent misoperation, the operating target is confirmed before the operation is begun. SURF (Speed Up Robust Feature) [69] is a widely used technique to determine the target from among the input images. Using SURF, characteristics are detected by major changes in brightness. The patterns of variation in brightness around the characteristic point are displayed as feature values comprised of 64-dimensional variables. The target is determined by selecting a template image with the most characteristic points (referred to as "matching key points" below) that match the feature values among the input images based on template matching. A feature of template matching using SURF is that high-precision target identification can be performed even if there is a difference in the distance and direction with regard to the object the time at which the input image or the template image is photographed.

With conventional image recognition techniques, including SURF, it is not possible to distinguish specific target objects from among different types of multiple target objects with the same shape. Yating et al. have developed a safety operation training support system for machinery using SURF [87]. Even this system does not assume the preparation of different types of equipment with the same shape. In the operating field in petrochemical plants, tools and materials may be temporarily placed in an area around operating targets, which may be photographed as an input image along with the operating target. Therefore, a method is needed for confirming operating targets among the different types of machinery with the same shape, with the assumption that materials have been temporarily placed near the operating target. It is difficult to confirm the operating target from among different types of machinery with the same shape based on their appearances alone.

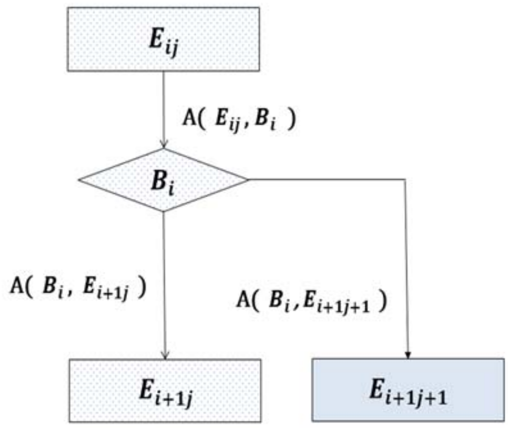

Figure 3.3 Operating procedure model with a conditional branch

Therefore, the operating target is confirmed using positional relationships with piping and other machinery that is photographed in the background of the input images. The matching key points are detected using SURF. Such key points are illustrated in Figure 3.4. They are detected in relation to operating targets, nearby piping, machinery, and temporarily placed equipment. Matching key points detected with regard to equipment placed temporarily are called non-conforming key points. When there are many such key points, there is a high possibility that the results of determining the template matching will be incorrect. Therefore, non-conforming key points are removed using the method described below.

The coordinates of matching key points in the input images and template images are shown by the following formula:

$$p_k = (i_k, j_k)\ , q_k = (u_k, v_k)\ \ (k = 1,2, \cdots, NK) \qquad (3.1)$$

Here, k is the matching key point serial number, p_k is the input image matching key point, q_k is the template image matching key point, and NK is the total of the matching key points. Next, the input image is superposed onto the template image, and the distance between the key points is found using the following formula:

$$L_k = \sqrt{(i_k - u_k)^2 + (j_k - v_k)^2} \qquad (3.2)$$

Then, the average value $\bar{L}$ of L_k and the standard deviation S are obtained using the following formula:

$$\bar{L} = \frac{\sum_{k=1}^{NK} L_k}{NK} \qquad (3.3)$$

$$s = \sqrt{\frac{1}{NK-1} \sum_{k=1}^{NK} (L_k - \bar{L})^2} \qquad (3.4)$$

Next, the non-conforming key points are removed using the approach of management limits from process management.

The maximum value UCL is established, based on $(\overline{L} + \alpha \cdot s)$. In this paper, the value of coefficient α is set based on prior observations and actual conditions. Matching key points p_k where $(L_k > UCL)$ are removed as non-conforming key points.

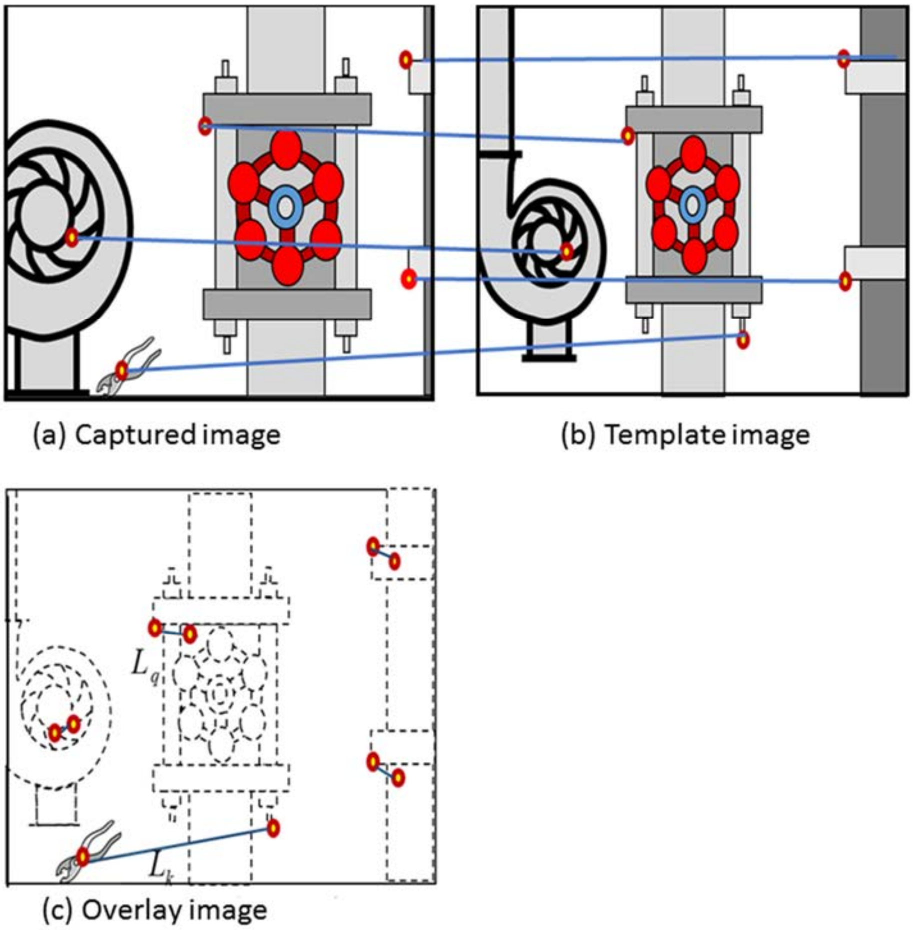

Figure 3.4 Summary of non-conforming key points

Figure 3.4 (a) shows the captured image, (b) shows the template image, and (c) shows the superimposed images, while matching key points are displayed in the image with a "○" mark. Temporarily placed equipment is not shown in the template image, so the distance between matching key points, where the feature values are given evaluations by chance, is considered to exceed the upper limit UCL and is deemed to be non-conforming key points.

3.2.3 Implementation of the proposed method

Using the two techniques described above, an operation information display system was constructed. The system of this organization is shown in Figure 12.

The operating target is confirmed prior to the start of operation by means of an operating target confirmation sub-system. After it is confirmed that it is the operating target by means of template matching, the operating details are displayed to the fieldman on the operating information display sub-system. The operating information display sub-system is installed with operating produced models. In accordance with the prior relationship of the operating procedure models, operating information within the event is displayed to the fieldman.

3. 3 Examples of application

The operating procedure manual is partially installed on the system for indirect desulfurization equipment (HDS). HDS is a hydrodesulfurization process that separates vacuum gas oil and distilled residual oil from crude oil using a vacuum distillation apparatus and separates and removes sulfur from vacuum gas oil using a metal catalyst.

3.3.1 Operating procedure manual standardization

HDS simulator plant malfunction countermeasure operations were targeted. A part of the operating procedure manual is shown in Figure 3.5. The operating procedure for dealing with vacuum gas oil (VGO) supply outages is described. Due to a VGO outage, the liquid surface level in the tank (D401) is lowered by the control room, a low alarm is sounded (liquid surface level: LC401), and LCV401 (liquid surface control valve) is fully opened. The tank (D401) is emptied due to the suspension of the supply of materials, and the temperature of the heating furnace rises.

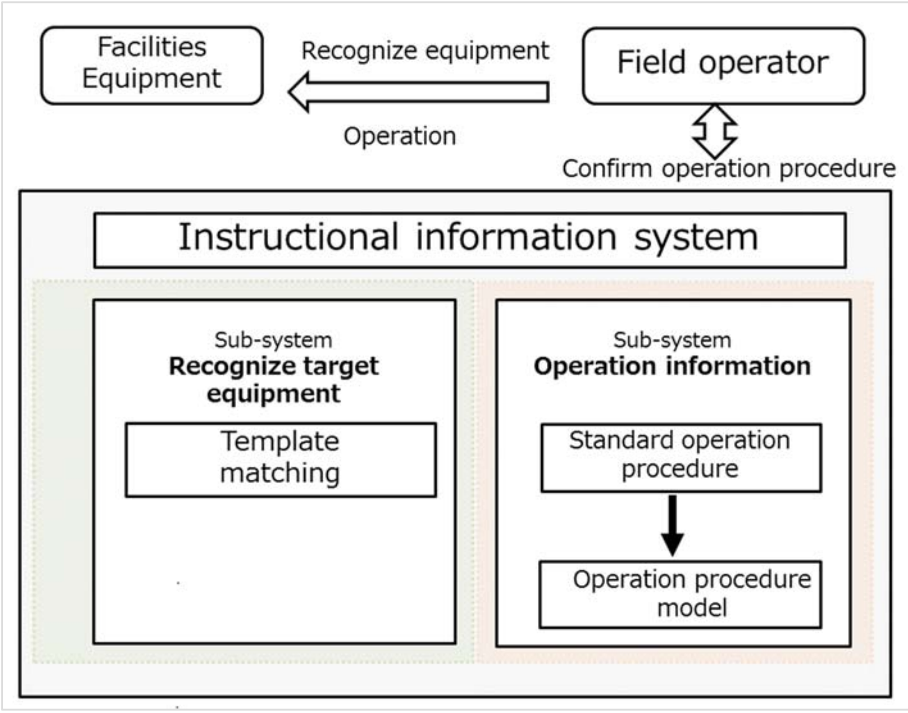

Figure 3.5 Instructional information display system

The operation of valve opening and closing is carried out by the fieldman to switch the circulation system over as a malfunction countermeasure. Mistaking the operating target will lead to a major accident. Field operation is conducted in consultation with the boardman. Figure 13 shows all countermeasure procedures, but this procedure manual does not provide any detailed information such as the distribution of roles between the boardman and the fieldman. The boardman is the main operator for 1 and 2, and the fieldman is the main operator for 3–5. Main operation 2 belongs to the boardman after main operations 3–5 have been completed.

401 VGO feed trouble Stopping raw material supply
Assume that a failure of the previous stage device occurs during steady operation of 100% of VGO supply

<table>
<tr><td>Failure situation</td><td>Corresponding status of control room</td></tr>
<tr><td>VGO feed stopped</td><td>Supply of feed material is stopped, and the level of D-401 drops.
1, D - 401 level drops,
LC 401 , low level alarm issued
2, LCV 401 is fully opened.</td></tr>
<tr><td colspan="2">1) Corresponding operation
Switch to internal circulation by site workers.
If it can switch to circulation while the level of the surge drum (D - 401) exists, it will not cause a serious problem. The temperature will rise as the charge amount of the reactor goes down so as not to cut off the fuel. Pay attention when the furnace temperature rise. If the supply of VGO recovers in about 1 to 2 days, circulate DVGO and wait.
2) Main operation procedures
①Decrease the reactor charge amounts FC 402 to FC 407 (to 120 kl / h).
②Squeeze the fuel (FC 406) in the heating furnace (F-401), lower the temperature TC 409 of the heating furnace to the point where it does not react (about 250 ° C.)
③Establish flow of liquid by circulation line and supply of DVGO
④Manual valve closing of VGO supply line
⑤Stabilize distillation tower
3) Points of the training
Switch to the circulation line until the surge drum becomes empty, to prevent the temperature rise of the heating furnace and suppress occurrence of accidents.
In general, note that the heat exchanger (E - 403) has a high risk of leakage due to heat shock.
① Switch promptly to circulation
② Reduce the inlet flow rate of the heating furnace and adjust the outlet temperature.
Do not change as narrow as possible the inlet flow rate of heating furnace as much as possible
③ Externally supplied VGO is close to 190 ℃, but since circulating DVGO is about 65℃, pay attention to temperature change at the furnace exit.</td></tr>
</table>

Figure 3.6 Operating procedure manual for malfunction countermeasures

The model operating procedure was produced after reorganizing the manual for the operating procedure shown in Figure 3.6, based on the proposed method. Only one operating target machinery exists in the event. Main operation 3 involves switching over two valves, so there are two events. Main operation 1 is E_{10}, main operation 2 is E_{60} and E_{70}, main operation 3 is E_{20} and E_{30}, and main operations 4 and 5 are E_{40} and E_{50}, respectively. The details of operation for each event were organized using 6W2H. The model of the fieldman's operating procedure can be obtained by extracting the events related to the fieldman. This model is shown in Figure 3.7. In this case, the "Who" is the fieldman. The operation is represented by four non-diverging events: E_{20}, E_{30}, E_{40}, and E_{50}. The operating details of each event are described below.

In event E_{20}, the valve (HV811) is the "What" and "open" is the "How." The operating details are presented to the fieldman in the following order:

E_{20}: Open the valve (HV811).

E_{30}: Close the valve (HV813).

E_{40}: Report to the boardman after stopping the manual valve.

E_{50}: Report to the boardman after confirming the distilling column.

Using event E_{20} as an example, the example screen presented to the fieldman is shown in Figure 3.8. The left window in Figure 3.8 shows the confirmation screen for the operating target. The upper-left confirmation button ① for the operating target is pressed before the start of operation. The image from the camera is displayed in input image window ②. The input image (still image) is obtained by pressing the photograph button ③. Next, by pressing the photograph target identification button ④, template matching is performed. The template image with the most matching key points is selected through template matching, which is shown in identification results window ⑤.

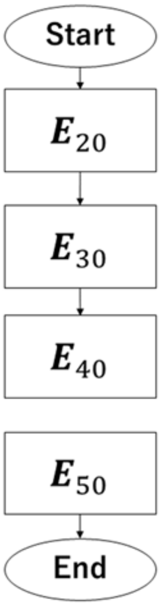

Figure 3.7 Field operator operating procedure model

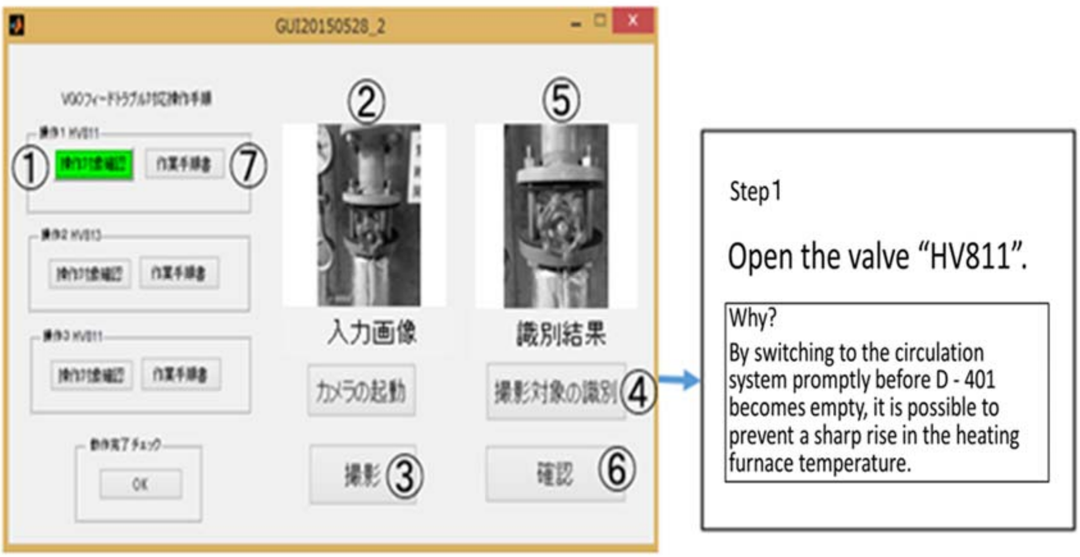

Figure 3.8 Operating screen of the proposed method

If the selected template image is the operating target template image, the background color of confirmation button ⑥ becomes yellow. If the selected template image differs from the operating target, the background color of confirmation button ⑥ becomes red. The input image must be retaken until the template image for the operating target is selected. Once the input image is confirmed as the operating target, operating procedure manual button ⑦ is pressed. When the operating procedure manual button is pressed, a new window is displayed in the lower-right of the same image that shows the operating details (Who, What, Why, How). The operating details for other events are shown sequentially according to the operating procedure model.

3.3.2 Confirmation of operating target

The technique of confirming the operating target was verified using a confirmation of the butterfly valves commonly used in HDS plants and other plants. Figure 3.9 (a) shows the input image of the operating target, and Figure 3.9 (b–e) shows the template image. The template image of the operating target is shown in Figure 3.9 (b). The three other template images are images of different valves located in that area, with the same shape as the operating target.

(1) Template matching using SURF

The characteristic points were found using SURF. The numbers of matching key points from each template are shown in Table 3.1. In terms of the number of matching key points, template image 1 is selected. This is the correct determination result. Next, the results of template matching are investigated in detail. The input image is imposed on the template image, and lines connecting the matching key points are found. Figure 3.10 (a) shows the lines that connect the matching key points to the input image and template image 1. Figure 3.10 (b) shows the lines that connect the matching key points in the input image and template image 2. In template image 1, qualitatively, the majority of the line segments are short and direction is unified. In contrast, the lines are long and disorganized in template image 2. These results are compared numerically. The average value and standard deviation of the length of the lines between the matching key points in the four template images is found. The results are shown in Table 3.2. The average value of the length of the lines in template image 1 is 41% or less of that of other template images.

Table 3.1 SURF Matching key points with SURF units (items)

	Image 1	Image 2	Image 3	Image 4
No. of shared key points	75	31	22	12

Table 3.2 L_k average value and standard deviation Units (pixels)

	Image 1	Image 2	Image 3	Image 4
$\bar{L}$	82.9	194.7	241.2	198
σ	95.1	106.6	95.6	114.2

(a) Input image

(b) Image 1 (Valve 1)

(c) Image 2 (Valve 2)

(d) Image 3 (Valve 3)

(e) Image 4 (Valve 4)

Figure 3.9 Input image and template image

(a) Image 1

(b) Image 2

Figure 3.10 Superimposed image (before removal of non-conforming key points)

Next, the non-conforming key points are investigated. The input image and template images are laid out horizontally. Figure 3.11 shows the lines connecting the matching key points from the input image and the matching key points from template image 1. The left half is the input image, and the right half is the template image. Figure 3.12 shows the matching key points from the input image and the matching key points from template image 2.

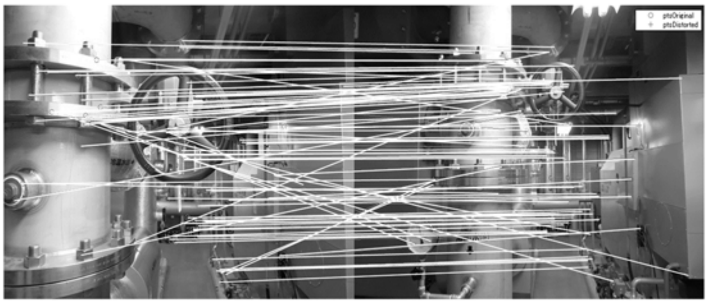

Figure 3.11 Matching key points in input image and image 1

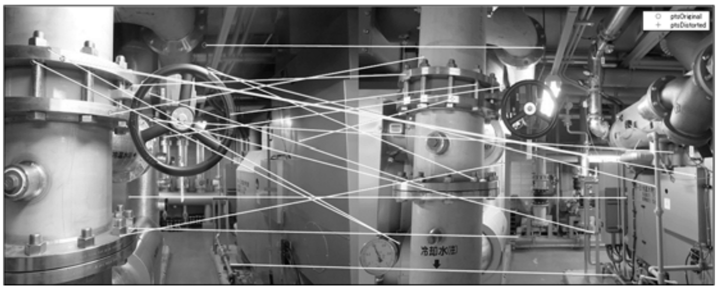

Figure 3.12 Matching key points in input image and image 2

In Figure 3.11 and Figure 3.12, the locations of matching key points are visually confirmed. Where the location does not match, such as when the location of the matching key point is a flange in the input image and a measuring instrument in the template image, it is deemed to be a non-conforming key point. In the input image, many of the detected matching key points are butterfly valve flanges or piping areas in the background passageways. In template image 1 too, many of the detected matching key points are butterfly valve flanges or piping areas in the background passageways. In template image 1, 66 of the 75 matching key points are consistent with the input image, and 9 are non-conforming key points. The proportion of non-conforming key points is 12% (9/75 × 100). In template image 2, many matching key points were detected in the piping area on the right wall. In all, 2 of the 31 matching key points are consistent with the input image, and 29 are non-conforming key points. The ratio of non-conforming key points is 93% (29/31×100). Therefore, this shows that template matching using the background based only on SURF produces many non-conforming key points.

(2) Removal of non-conforming key points

The maximum value UCL is found with coefficient α = 1.0 to remove the non-conforming key points, based on Table 2. The results are shown in Table 3.3. Key points where $L_k > UCL$ are removed from the template images. The number of matching key points after removing the non-conforming key points is shown in Table 3.4. There is no change, and template image 1 is still selected.

To examine the template matching results in detail, the input image is superimposed on the template image. Figure 3.13 (a) and Figure 3.13 (b) show lines that connect the matching key points. Qualitatively, in template image 1, the lines are mostly unidirectional.

(a) Image 1

(b) Image 2

Figure 3.13 Superimposed image (after removal of non-conforming key points)

Table 3.3 Maximum values for removing non-conforming key points UCL

Unit (pixel)

	Image 1	Image 2	Image 3	Image 4
UCL	178	301	336	312

Table 3.4 Number of matching key points after removing non-conforming key points

Unit (items)

	Image 1	Image 2	Image 3	Image 4
No. of shared key points	66	25	17	11

Table 3.5 L_k average value and standard deviation after removing non-conforming key points

Unit (pixel)

	Image 1	Image 2	Image 3	Image 4
$\bar{L}$	55.3	156.4	207.2	168.9
s	40.9	75.4	81.1	56.4

However, in template image 2, lines connecting the matching key points are not organized. The results are the same as prior to the removal of non-conforming key points. To investigate this qualitatively, the average value $\bar{L}$ of the length of the line between matching key points and the standard deviation "s" are found. The results are shown in Table 3.5. The average value $\bar{L}$ of the line in template image is 35% or less of that of other template images, and the gap is greater than before the removal of non-conforming key points.

Next, the input image and the template image are lined up, and the locations of matching key points are visually confirmed. In template image 1, the locations of 63 of 66 matching key points are consistent. The number of non-conforming key points is reduced from 9 (12%) to 3. The ratio of non-conforming key points is reduced to 4% (3/66 × 100). In template image 2, the locations of only 2 of 25 matching key points are consistent. The number of non-conforming key points is reduced from 29 to 23. The ratio of non-conforming key points is reduced to 79% (23/29 × 100). Based on the above results, the non-conforming key points are reduced by 10% or more in template images other than the operating target.

(3) Evaluation criteria for non-conforming key points

From the above inspection, to establish the removal standard for non-conforming key points, coefficient α was set at 1.0. After removing the non-conforming key points and when the coefficient α was change, the number of matching key points was investigated. The results are shown in Figure 3.14.

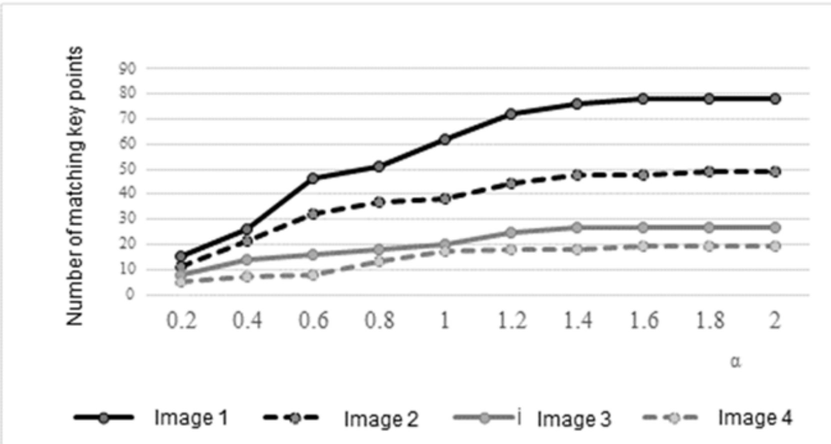

Figure 3.14 Number of matching key points after removal of non-conforming key points

In this example, even if coefficient α is changed, the results of template matching do not change. When the value of coefficient α is 1.4 or more, almost no non-conforming key points are removed. When coefficient α is 0.4 or less, several matching key points are removed and the difference in the number of matching key points in the template images is greatly reduced. For that reason, the method of decided coefficient α requires that a realistic value be set based on sufficient prior observation. Method-setting coefficient α remains as a challenge for the future.

The results discussed above demonstrate that the operating target can be confirmed from among different types of machinery with the same shape using the background based on the proposed method.

3.4 Conclusion

In this paper, the main target was to prevent human error from being a main cause of accidents in petrochemical plants.

(1) A technique was proposed that would reorganize the paper format operating procedure manuals from the perspective of preventing human error and would enable standardization for incorporation on computer systems.

(2) An image recognition technique was proposed that would enable the confirmation of operating targets without using the machinery of special assistance such as AR markers. The background of the operating target installation area and the positional relationship with other machinery were used for confirming the technique.

(3) By incorporating the two techniques into a computer system, an information display system for plant operations was developed and system performance was verified through the application of examples.

Note) The “HDS Simulator” malfunction sheet was referred to in this study from Omega Simulation Co., Ltd.

Chapter 4 Instructional information and sharing knowledge

4.1 Introduction

Improving the safety and reliability of chemical plant is essentially important for the safety environment for workers and local residents. Consequently, a number of safety activities, countermeasures, and assessment techniques have been proposed. We need the way for detecting potential risks before an accident or disaster occurs. In addition, a safe process design is necessary for preventing human error. Control problems are increased in both software and hardware as the economic situation changes [88]. In a chemical plant, operators must handle their own areas in order to ensure the safe operation of all plant components. There are two types of operators: field operators and board operators. Field operators are responsible for operating equipment in the field. Board operators control refineries from a control room. In order to achieve smooth operation, it is needed cooperative work in both areas [88]. Accidents often occur from human factors, including misjudgement and miscommunication. Accidents also often occur in non-steady-state operation [89]. When an accident or disaster, emergency response is needed. Operators have to make accurate and quick decisions in spite of being in high pressure situations [88]. At present, operational guidelines and procedures have not been fully developed. Accurate judgements and the corresponding operational steps are very important in order to prevent the escalation of the accident [89]. However, opportunities for technology inheritance for young operator, especially safety training and education have decreased over recent years. We are concerned that the flexible response capability of workers has also reduced with the retirement of skilled workers. In this study, we propose a system to provide instructional information for field operators by using augmented reality (AR) and image recognition technology in chemical plants. AR can enhance real-world environments by using virtual objects such as computer graphics [90]. The system can distinguish between operation target equipment and others by image recognition technique based on SURF (Speeded up Robust Features) Algorithm. [69] The field operators can confirm the required operation procedures in the field. Furthermore, the operator can recognize the proper operating equipment by using a camera-equipped tablet PC. Our system has been designed to support chemical plant operators in making quick decisions and in taking the correct operating steps. The concept of the proposed system is shown in Figure 4.1. To convey accurately indication information of the work, it is useful to recognize by vision in addition to the output information by voice. It can support chemical plant operators to follow correct operating procedures without human error.

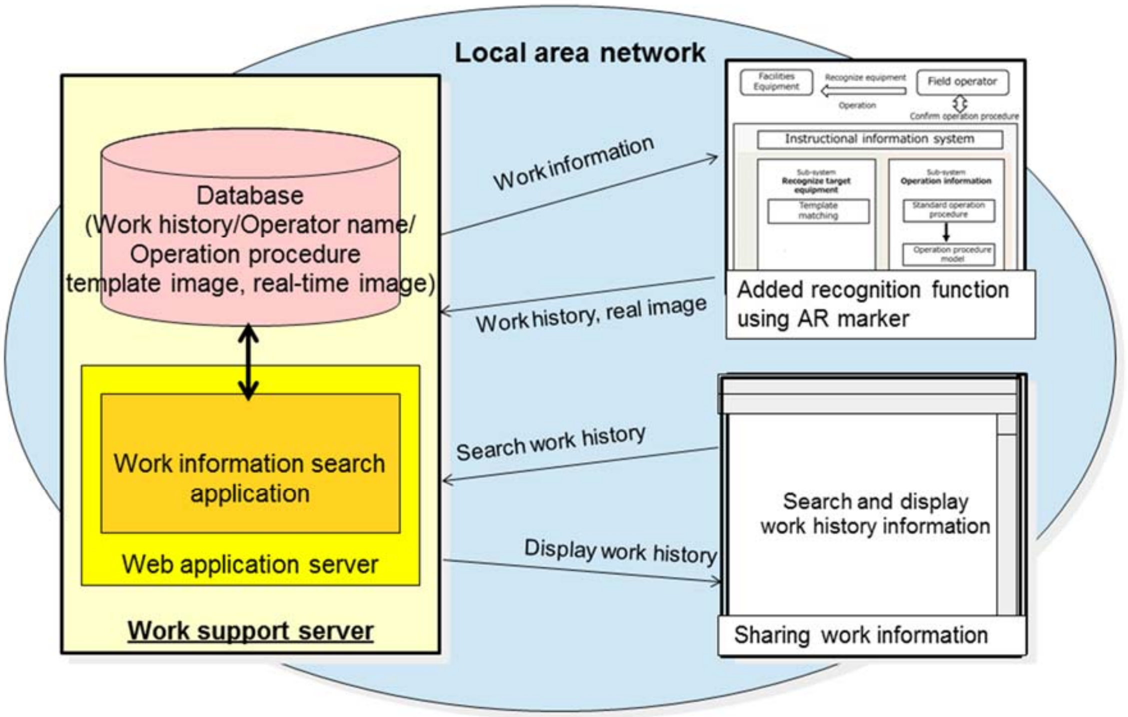

Figure 4.1 Concept of the instructional information System

4.2 Purpose and Approach

In chemical plants, a large amount of dangerous chemical fluids that flow through into the pipe and the equipment are arranged in close proximity. Board operators manage the process until the product from raw materials based on the information from the distributed control system (DCS). Board operators instruct the field operators on the necessary operations by monitoring the plant conditions. When an alarm is issued, field operators perform according to instructions from control room. Operating instructions on the site is a qualitative indication, not a quantitative data, for example “Turn the valve to the right”, through the voice of the board operators. Also, due to the installation of similar aggregating pipes and valves, there is a risk of serious damage occurring due to operate wrong valve. In recent years, immature operators are being forced to handle complicated facilities with fewer people due to the aging workforce situation. As a result, human error has been increasing in chemical facilities [66]. The proposed system shows the relevant operating procedures and accurate equipment information using AR and Image recognition. The field operators captured the equipment through the camera of tablet PC. The name of equipment and operating information are shown in the display. With advances in computer technology, AR can function in ways that enhance one’s current perception of reality [65]. It does so by incorporating computer vision and object recognition, so that the information about the real world of the user becomes interactive and digitally alterable. Virtual information can be overlaid on the real world. The AR marker shows an image of a set pattern, which is indicator for specifying the installation site and displaying additional information, the name of equipment and process condition etc. [65]. The operator identifies target equipment with the camera, and can confirm the correct operating procedure on the tablet PC. The work information is displayed to the operator first, after the task has been completed, the next work procedure is presented by updating the plant information. Human errors often occur when a field operator works alone or in a non-steady-state operation [84]. The purpose of this study is to support the work of young, immature operators and to reduce human error.

4.2.1 Detection of AR marker in the system

In this study the AR toolkit is used to implement the technology with AR markers. ARToolKit is a software library developed for the research of AR, published as open source in 2015. The most necessary mechanism in the processing of the AR application is the processing of detecting the AR marker. This process, which is constantly being done during application execution, consists of two tasks.

1. The system acquires the AR marker from the captured image.
2. The system identifies the marker that most closely matches by comparing "image seen by marker" and "pattern file".

In order to execute the AR application, the system requires "AR marker" to decide "output position" of 3-dimensional object and "pattern file" registering the marker and bitmap pattern. The pattern file of the marker to be identified. It is necessary to create a file conforming to ARToolkit. The file name should be "marker $ {id} _patt.dat". $ {id} inserts "operation id". Examples of AR markers and bitmap patterns are shown in Figure 4.2 a, b.

(a) ARmarkers

```
234 235 240 233 240 234 240 235 240 237 240 238 240 240 240 232
229 240 240 240 240 240 240 240 240 240 240 240 240 240 240 228
227 240 240 240 240 240 240 240 240 240 240 240 240 240 240 239
240 240 240 240 240 240 240 240 240 240 240 240 240 240 240 240
236 240 240 240 240 240 240 240 240 240 240 240 240 240 240 240
234 240 240 240 240 240 240 240 240 240 240 240 240 240 240 240
236 240 240 240 240 240 240 240 240 240 240 240 240 240 240 240
231 240 240 240 240 240 240 240 240 240 240 240 240 240 240 240
229 240 240 240 240 240 240 240 240 240 240 240 240 240 240 240
225 149 240 240 186 216 225 174 240 240 240 237 238 240 240 240
150 107 238 231  75 208 115 147 238 228 223 226 237 180 226 240
150  62 181 213  62 187 113 169 197  72  29 237 120  50  53 207
149  63  47  78  53 184 113 101 142   5 150 150  45 217 186  83
121  84 220 222  58 180 121  92 128 109 237 124 155 232 161  64
149  71 240 240  76 210  98 109 122 108 240 129  51 119 161 155
...
```

(b) Bitmap pattern

Figure 4.2 Examples of AR markers and bitmap patterns

AR marker recognition procedure in the system shows followings.

1. Set the input image to M_0
2. Input image M_0 is converted the grayscale image M
3. Perform binarization processing
   A threshold value K is set. If all the pixels in the image M have luminance values $p(i,j)$ $(i = 1,..,m,\ j = 1,..,n)$ greater than or equal to K, set 1. It is set to 0 when the luminance value is less than K.

   The image after binarization processing is represented by B , and the luminance value of each pixel $B(i,j)$ in image B is represented by $g(i,j)$.

   $g(i,j)$ is shown in Equation 4.1.

$$g(i,j) = \begin{cases} 1 : p(i,j) \geqq K \\ 0 : p(i,j) < K \end{cases} \quad (4.1)$$

4. Labeling is performed to detect the region of the AR marker according to the 4 consolidation method
   In the binarized image, label of pixel $B(i,j)$ is denoted by ℓ, that is $S(i,j) = \ell$.

   In the 4-consolidation method, labels of pixels adjacent to the noted pixel $B(i,j)$ are given by the following equation 4.2.

$$\begin{pmatrix} g(i,j+1) = g(i,j) \rightarrow S(i,j+1) = \ell \\ g(i,j-1) = g(i,j) \rightarrow S(i,j-1) = \ell \\ g(i-1,j) = g(i,j) \rightarrow S(i-1,j) = \ell \\ g(i+1,j) = g(i,j) \rightarrow S(i+1,j) = \ell \end{pmatrix} \quad (4.2)$$

5. Bounding Rectangle
   Let $I_1(\ell)$ be the minimum value on the i axis of the area with label ℓ and $I_2(\ell)$ for the maximum value.

   Also, the minimum value on the j axis is denoted as $J_1(\ell)$ and the maximum value is denoted as $J_2(\ell)$.

Let $W(\ell)$ be the width in the horizontal direction of the area of label ℓ and $H(\ell)$ be the height in the vertical direction in equation (4.3)

$$\begin{pmatrix} W(\ell) = I_2(\ell) - I_1(\ell) + 1 \\ H(\ell) = J_2(\ell) - J_1(\ell) + 1 \end{pmatrix} \quad (4.3)$$

6. Identify the AR marker
   When the label of the area where the size of the circumscribed rectangle is the maximum is ℓ, this area is judged to be the area of the AR marker.

   Next, the region of the AR marker is divided into $(n \times n)$ regions, and the average luminance value $q_u (u = 1, \ldots, n^2)$ of each region is obtained.

   Also, the AR marker image of the number r ($r \in \{1,2,\ldots\} = A$) is divided into $(n \times n)$ regions and the average luminance value $Q_u^r (u = 1, \ldots, n^2)$ in advance.

   The difference between the luminance value of the region of the label ℓ and the luminance value of the AR marker number r in the input image is expressed by the following equation.

$$E_r = \sum_{u=1}^{n^2} (Q_u^r - q_u)^2 \quad , (r \in A) \quad (4.4)$$

   Next, the AR marker that minimizes the squared error given by equation (4.4) is determined by equation (4.5) and it is determined as the AR marker in the input image.

$$E_r^* = min\{E_r | r \in A\} \quad (4.5)$$

4.3 Instructional Information System

4.3.1 Outline of Instructional Information system

The proposed system consists of two subsystems and database; operating procedure system and equipment recognition system, operation support database. Plant information for the operating procedure is stored in the operation support database and presented as required. Operators can confirm the procedures and recognize the target equipment using the system through the camera-equipped tablet PC.

The work flow of using this system is the following steps:

1. Check the displayed procedure on the tablet screen.
2. Search the equipment based on the instructions of the system.
3. Recognize the operation target device.
4. Operate the target device.
5. Check the operation and proceed to the next task.

After the operation finished, the work information is stored in operation support database. This system can make operation report as requested for safe management for chemical plant.

4.3.2 Operating Procedure System

Traditionally, the standard operating procedure (SOP) is created on printed paper. Usually, SOP is displayed in the form of a list, with no detailed information provided on the timing and the operation. Operating manuals lack descriptions of operational targets and their location through photos or figures. The instructional information that is presented to workers is, therefore, not considered to be sufficient. Conventional SOP is hard to understand intuitively. In order for the operator to perform alone without a trainer, considerable money and time must be spent. Furthermore, the retirement of skilful workers is advancing in Japan, their experience and skills are not being sufficiently transferred to young workers. Moreover, skilled workers may not remember the procedures of non-steady-state work. Operating procedure systems compensate for the gaps in knowledge of safe operation. First, work procedure is indicated by the system. The field operator operates the equipment with reference to the work procedure outlined by the system. The field operator then refers to the tablet PC and advances to the next task. In this study, we propose ways to present operators with the correct operating procedures that can be used in the field of chemical plants.

4.3.3 Standard Operating Procedures

Existing operating procedures are presented in a list. In order to systematize the operating procedures on paper, the contents of the procedure should divide into steps. The SOP contains too much information. Therefore, there is a need to clearly describe the role of the workers. Accordingly, we sorted the information by using the 6w2h method. 6w refers to “what”, “who”, “when”, “where”, “whom” and “why”; 2h refers to “how” and how many. [100] The procedure of each operation is further divided and described in length it can be understood at once.

4.3.4 Operation Support Database

The created procedures, plant conditions, and template photos of the equipment are stored in operation support database. After work by using this system, operation information is stored in the database. The information can be safety information for safety management data of the plant equipment. Field operators can request procedures and equipment information from the database by operating the tablet PC. The information in this database is updated by performing the operation of the plant in the simulator; this can be presented to the worker. The next procedure is updated for display in the system after the completion of the first procedure to prevent a slip in operation. The information in the database is thus capable of being modified when necessary. And it may be further expanded.

4.3.5 Equipment Recognition System

The equipment recognition system identifies equipment using the camera on the tablet PC. AR markers and image recognition based on SURF are used to recognize the plant equipment; the system then presents the target device to the field operator. The AR marker, in an Equipment recognition system, is an indicator for specifying a position to display additional information and the image of a set pattern. When the AR system recognizes the marker or template matching, it can display information that has been specified so as to overlap with the real image. Simple black-and-white graphics or QR codes are often used as AR markers. There are many similar equipment, such valves and pipes, in a chemical plant. When installing a marker on the operation target device, the system is able to identify and determine the correct operational target and the operating procedure is presented. In addition, this system has a function to recognized target or not using AR marker or image recognition technology switching automatically. There is huge amount of the plant equipment, so it can't to make and put AR marker of all equipment in facilities. AR marker can use for recognition the equipment area. The proposed system can recognize the target equipment using both AR marker and SURF algorithm. The workflow utilizing the system is performed based on SOP to be accessed from the database. The operator checks the procedure in the field and identifies the AR marker of the target equipment with the help of the tablet PC camera. When the camera captures the correct target equipment, the device recognition system displays a captured photo. If field operator tries to operate the wrong equipment, the system shows a red edge around the photo. And a captured photo is OK on the tablet PC indicates green edge around the photo of the target equipment. After the camera detects the target equipment, the information on the equipment is displayed, followed by the operating procedure. Then the field operator can perform along with the procedure displayed. If the operating instructions cannot be understood, the operator can refer to additional information in the system. When the camera recognizes the operation target equipment by the AR marker, the name of the target equipment is presented on tablet PC. Figure 4.3 shows the system screen that shows using AR marker and image recognition based template matching.

Figure 4.3 Operation procedures and target device recognition using AR and SURF technology

4.4 Operating Experiment of the HDS Plant Procedure

This system is supposed to the SOP of the HDS process. This process including the reaction that comes with hydrogen separation and the removal of sulfur content from petroleum under high temperatures and high pressures; it also involves producing products with low kerosene and sulfur content, and light oils. In this experiment, our system was applied to the field work. In this paper, we referred to an operating procedure that had experienced Vacuum Gas Oil (VGO) charge pump failure trouble. The overview of the corresponding operations is followings,

1. The field operators need to switch from the main pump to the spare pump very quickly.
2. It is necessary to pay attention to the rising temperature of the furnace, due to the rise in temperature of the reactor.

3. A board operator should operate the DCS using caution, monitoring any change in the temperature of the inflow and outflow of the furnace.
4. A field operator should confirm the level of tanks D-402 and D-406 to prevent a rapid decrease liquid level.

In order to present the procedure on the system screen of left side, the photo of the target equipment shows right side on the screen on the tablet PC. Figure 4.4 shows screen shot of the development instructional information system.

4.4.1 Operating procedure

Operation procedures using this system are conveyed based on the progress of the work. Procedural information is written using Extensible Markup Language (XML). XML defines a set of rules for encoding documents and allows users to specify their own tags. It is possible for users to create their own meaning, structure and hierarchy in a unified manner. XML is also useful for creating files to store data [88]. The operating procedure to be used in this system. It is divided into steps <Step>, the ID information of each device <Target>, name <Name> and the associated markers <Marker>. By using XML, documentation can be easily created, changed and appended.

Figure 4.4 The proposed system recognize the target equipment

4.5 Discussion

In this paper, we proposed a system to provide instructional information for field operators by using AR and image recognition technology for chemical plants. By using these technologies, this system has made it possible to accurately recognize target equipment. The operator can recognize target equipment/area with the help of a camera-equipped tablet PC using AR marker or using image recognition technology of the system. The field operators can detect the correct equipment to perform procedures on and more easily differentiate between similar aggregating equipment, such as pipes and valves. Thus, the system can reduce the risk of serious accidents caused due to operators mistaking the device to be operated. After the procedure is completed, the next procedure is displayed by updating plant information. The number of equipment operated by the field operator is managed by the board operator in the control room. In addition to presenting detailed plant information, the function of this system should expand to include presenting instructions to board operators as well. In future, this system can be implemented with the actual controls and systems, and by using real plant data. Inherited technology and past accomplishments are essential factors in enhancing competitive production. Figure 4.5 shows the operation report using the function of proposed system. The information on this report can use for risk communication and risk management. The proposed system takes down the issue of human error by recognizing correct equipment, presenting relevant information, and having a confirmation function to prevent erroneous operation.

Figure 4.5 The operation report using the function of proposed system

4.6 Conclusion

In this study, we developed an instructional information system using AR and image recognition technology for chemical plants. This information system can indicate real-time operating procedures and accurate equipment information for field operators. In chemical plants in Japan, there have been rapid generational changes in the workforce. The skillful worker's technique and knowledge are being gradually lost. Inherited technology and past accomplishments are essential factors in enhancing competitive production. Human errors often occur when a field operator works alone or performs non-steady-state operations. This system can reduce human error by recognizing correct equipment, presenting relevant information, and having a confirmation function to prevent erroneous operation. In order to prevent an escalation of the accidents, the correct operation must be performed without any human error. The proposed system can support operators achieve this level of accuracy.

Furthermore, the system can also be used for safety education and training for young plant operator. The proposed system is expected to aid the next generation of operators in the field and help clarify non-steady-state operations.

Chapter 5 Information-sharing and distance cooperative work

5.1 Introduction

Preventing accidents in chemical plants is crucial to protecting the safety of employees and local residents. However, the number of accidents that occurred from 1989 to 2014 has been increasing, and several accidents at large industrial facilities have occurred continuously. Detailed information on the accident trend in chemical plants was published in the report “Liaison Committee for Municipalities and Agencies Reviewing Measures for the Prevention of Industrial Accidents at Petrochemical Complexes, etc.” The report was compiled via a Joint Press Release with the Fire and Disaster Management Agency and the Ministry of Health, Labor, and Welfare of Japan [1]. In FY2014, there were 253 accidents reported by 697 establishments in special disaster prevention areas such as petrochemical industrial complexes, totaling 24 cases more than the previous year. Of the total number of cases, 98 (39.0%) were due to human factors,140 (55.3%) were due to physical factors (e.g., corrosion, equipment failure), and 15 (6.0%) were due to disasters such as earthquakes, arson, and others. As causes of industrial accidents, there are many types of human errors, such as cognition/confirmation mistakes, misoperation, and misjudgment by employees. In terms of the number of accidents in 2014, 58 of the cases (23.0%) caused by human factors were due to misoperation and insufficient operation confirmation. In a cognitive/confirmed mistake, employees receive misinformation; thus, when they communicate with their peers, the information is not accurately conveyed, and the necessary confirmation is not performed. Misoperation refers to an erroneous operation that is executed habitually, that is performed due to fatigue or strain, or when a similar device (valve) is operated by mistake. Misjudgment refers to an erroneous judgment that is made based on a similar successful experience from the past, a judgment that is made based on the wrong information, a judgment that is made without understanding the meaning of the work, etc. [83]. There are numerous contexts surrounding accidents caused by human factors [90,91]. In order to clarify the scope of the application of the system proposed in this paper, a specific onsite operation was used: equipment operations such as valves and pumps are cooperatively performed by onsite operators (hereinafter: field operators) and control room operators (hereinafter: board operators) who are in charge of monitoring/remote control from the control room [88]. The device operation is performed according to the operating procedure manual. Voice communication through paging is mainly used for communication between the control room operator and field operator. In voice communication, erroneous judgment due to mistakes, misunderstanding, and cognition/confirmation errors is likely to occur by hearing incorrectly. In particular, petrochemical plants are prone to misoperations due to similarly shaped equipment such as various valves and piping that have different contents but can be mistaken for one another. Achieving a smooth operation requires cooperative work in both areas [88]. At the present, operation procedures in case of non-steady situation have not been fully developed. When accidents do occur, accurate judgments and their corresponding operational steps are very important to preventing accidents from escalating [89]. Control problems in both software and hardware have been increasing as the social situation changes, and we need better ways to detect potential risks and use a safe process design to prevent human error [91,92]. Figure 5.1 Shows the concept for the proposed system. Here, information about the cooperative work between field operators and board operators is more accurately conveyed because it contains a visual element in addition to the output information given through voice paging. In addition, the system proposes a method for sharing plant information to communicate. The proposed system aims to help chemical plant operators share correct operational information without human error.

5.2 Purpose and approach

One of the main causes of accidents in chemical plants is when the workload per employee increases due to labor-saving cost schemes. This has increased the possibility of erroneous operation and erroneous judgment by field operators due to operators' fatigue and lack of safety education [89]. Hara and Kuwabara [66] and Fumoto et al. [94] developed an operation support system using augmented reality technology; it was developed as a measure to prevent accidents caused by human factors. Using augmented reality technology, it confirms the operation target from among a large number of devices; however, it often required to use auxiliary equipment such as AR (Augmented Reality) markers and IC (Integrated Circuits) tags. Setting AR markers/IC tags for all valves and piping of a chemical plant requires enormous labor, time and cost, and is not a realistic measure. Yating et al. [88] developed the system for practical skill training using image recognition technology.

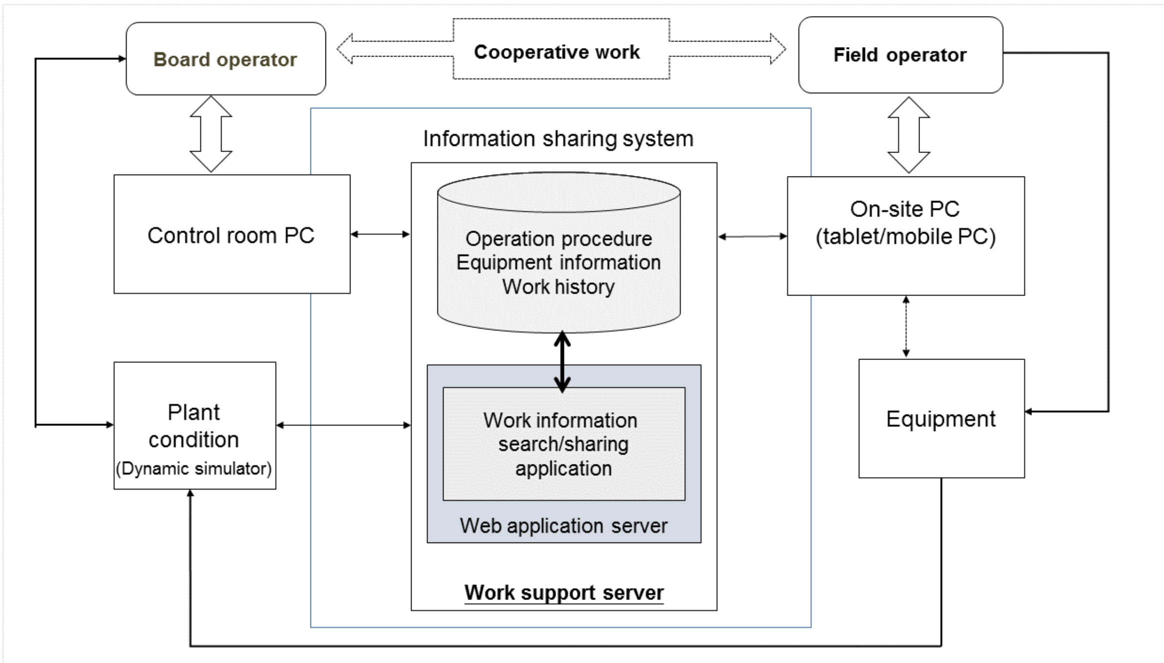

Figure 5.1 Concept of the proposed system

The present system considers sharing the operational information that is required to prevent misoperation and misjudgment onsite. In this study, it is used a dynamic plant simulator instead of a real chemical plant to reproduce the behavior of the plant. Plant operators can use tablet PCs in the field or desktop PCs in the control room. The proposed system can display information on the tablet PCs that have been standardized to include various operational procedures under regular conditions as well as during emergencies. The plant information is stored in a database that can be accessed and used as needed. The field operators can communicate with the control room about ongoing situations using the camera included in the tablet PC. In many chemical plants, onsite workers cannot quantitatively know the degree of a valve opening, and in order to know whether the work they did was appropriate, they must contact the control room. To solve this inefficiency, in this system, the process value of the plant simulator is routed to the tablet PC [94]. There are three important aspects of using this system: safety responsibilities concerning individuals, sharing information to gain mutual understanding and willingness between the board operators and the field operators, and promoting the inheritance of technology and safety knowledge. These things should be stimulated by supervisors and higher management. In addition, by using this system, it is possible to construct a cooperative work environment featuring virtual connection.

5.2.1 Clarification and classification of operation information

This section describes how the system facilitates communication between onsite work and control room work. By sharing real-time onsite information, a cooperative work environment between the board operators and the field operators is established. The architecture of this system is shown in Figure.5.2.

In order to implement the system, the information that is essential to the running of the chemical plant needs to be clarified and classified:

1. Standard information.

   This refers to concretized information such as operation procedures and P&ID diagrams. This static information will not change regardless of the passage of time during work.

2. Onsite images.

   Real-time onsite situation is captured by the camera in the tablet PC. This is dynamic information that changes in real time.

3. Sensor data of the dynamic simulator.

   These data convey changes in the plant conditions depending on the onsite and control room work.

4. Communication for working.

   Communication requires interactivity; here, instructions and reports change according to the progress of the work and the passage of time.

Instructions for initial corresponding are controlled by the board operator who works in the control room. This classification illustrates that the information necessary for plant operation includes fixed information, dynamic information, and interactive information. For this reason, the system was designed using an input/output method, which makes it easy to retrieve information. The static information is already stored in the database, and the sensor data from the simulator are stored in the database via a web application that is then displayed on the operators' tablet PC.

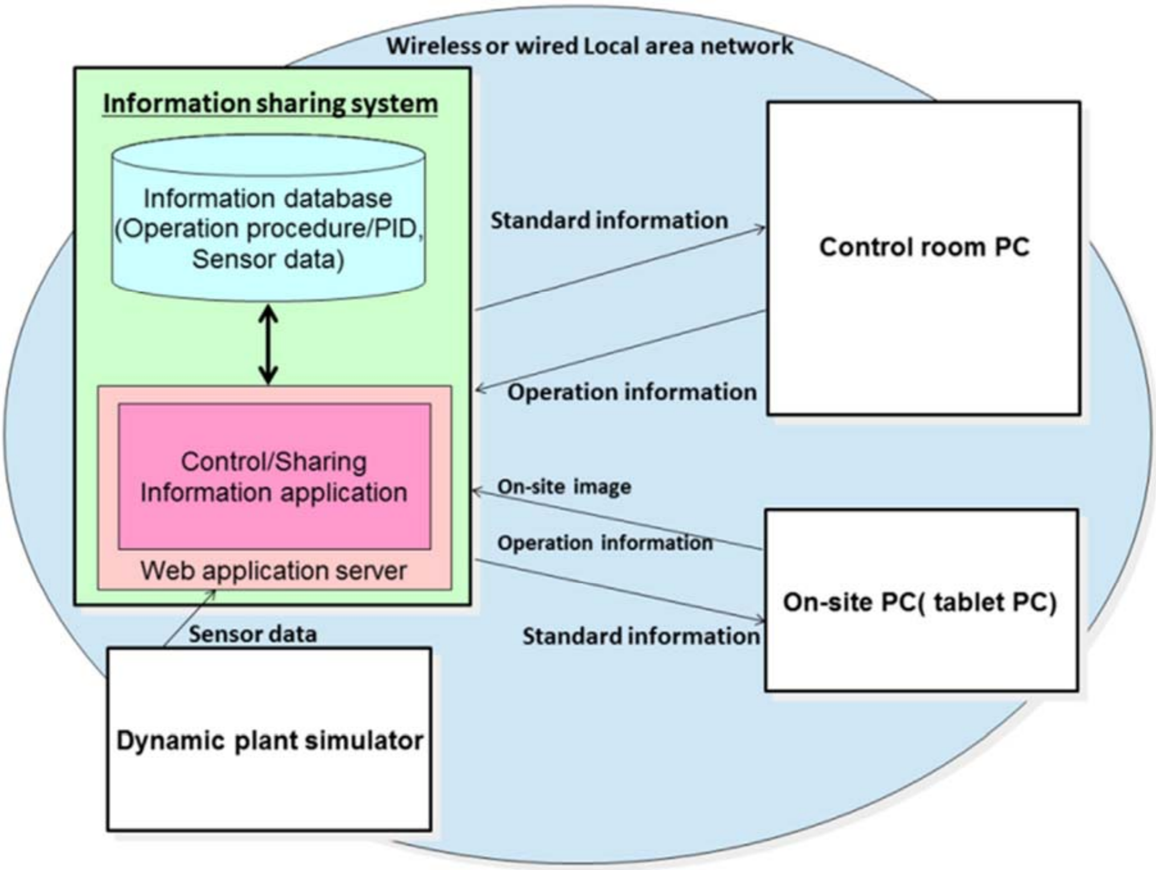

Figure 5.2 Information-sharing system architecture

5.2.2 Improved safety using the cooperative work environment in the proposed system

In the case of onsite work, when a work instruction is transmitted from the control room, a situation report is created onsite. When working with voice information alone, this interaction is usually repeated several times. Because operators are unable to see the site from the control room, they cannot confirm whether the workers onsite did the job correctly and safely. Also, from the work site, it is necessary to work while confirming to the control room how much to operate to prevent hearing mistakes and misjudgment. By standardizing the operation procedures in chemical plants, the field operators' and the board operators' roles are clarified [95]. Figure 5.3 shows the flow of work in terms of role sharing between board operators and field operators. Activity of igniting the burner due to trouble with the heating furnace is used as a model. Communication is important to the progress of the work. If communication between workers is poor, due to misunderstandings the activities may not follow well the regular flow and become entangled. The field operator cannot check the distributed control system (DCS) onsite, greatly increasing the likelihood of human errors. In order to ensure the safety of the working environment, the work must progress smoothly. When using the proposed system, the work progress changes, as shown in Figure 5.4.

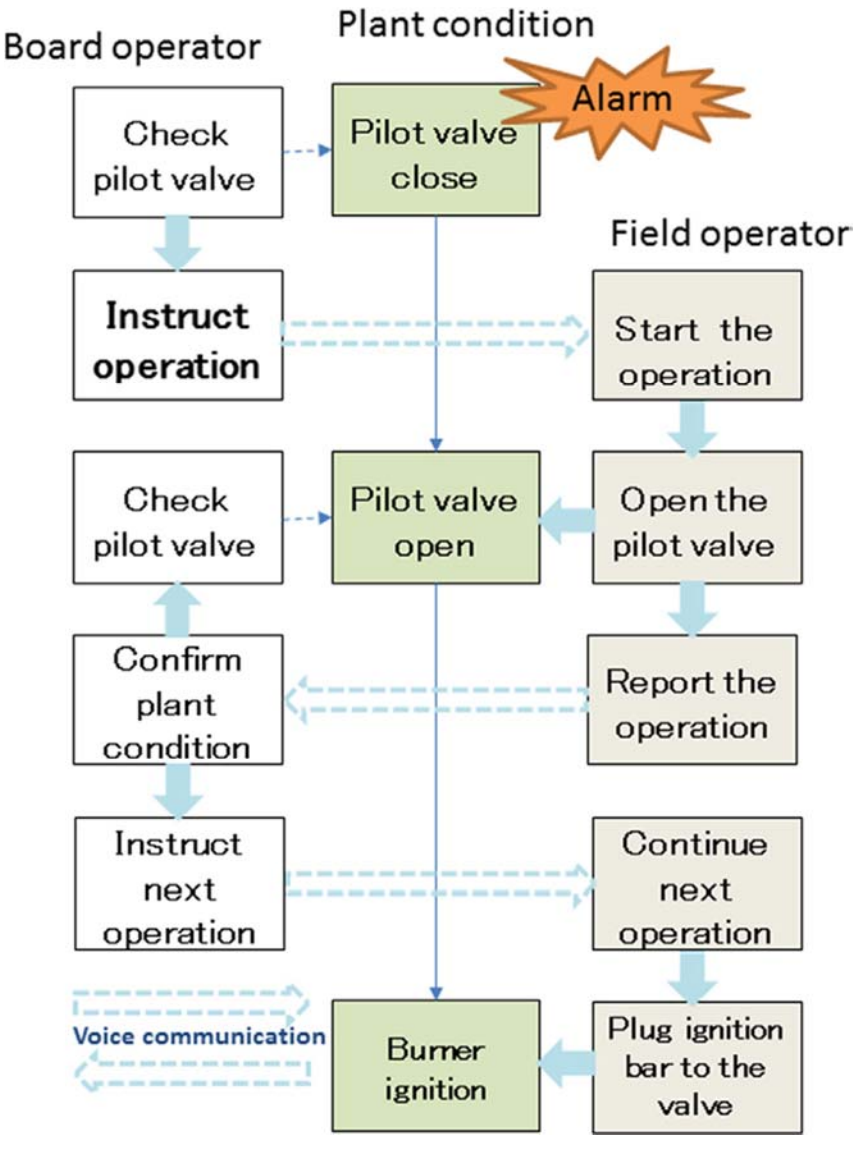

Figure 5.3 The flow of the cooperative work

Here, a cooperative work environment is constructed by complementing voice communication with realtime images and text messages (i.e., the plant condition data). In this research, the information of the dynamic plant simulator is used instead of the actual operation data of the chemical plant. It is extremely useful for workers to understand realistic plant conditions in order to support a safe working environment [84].

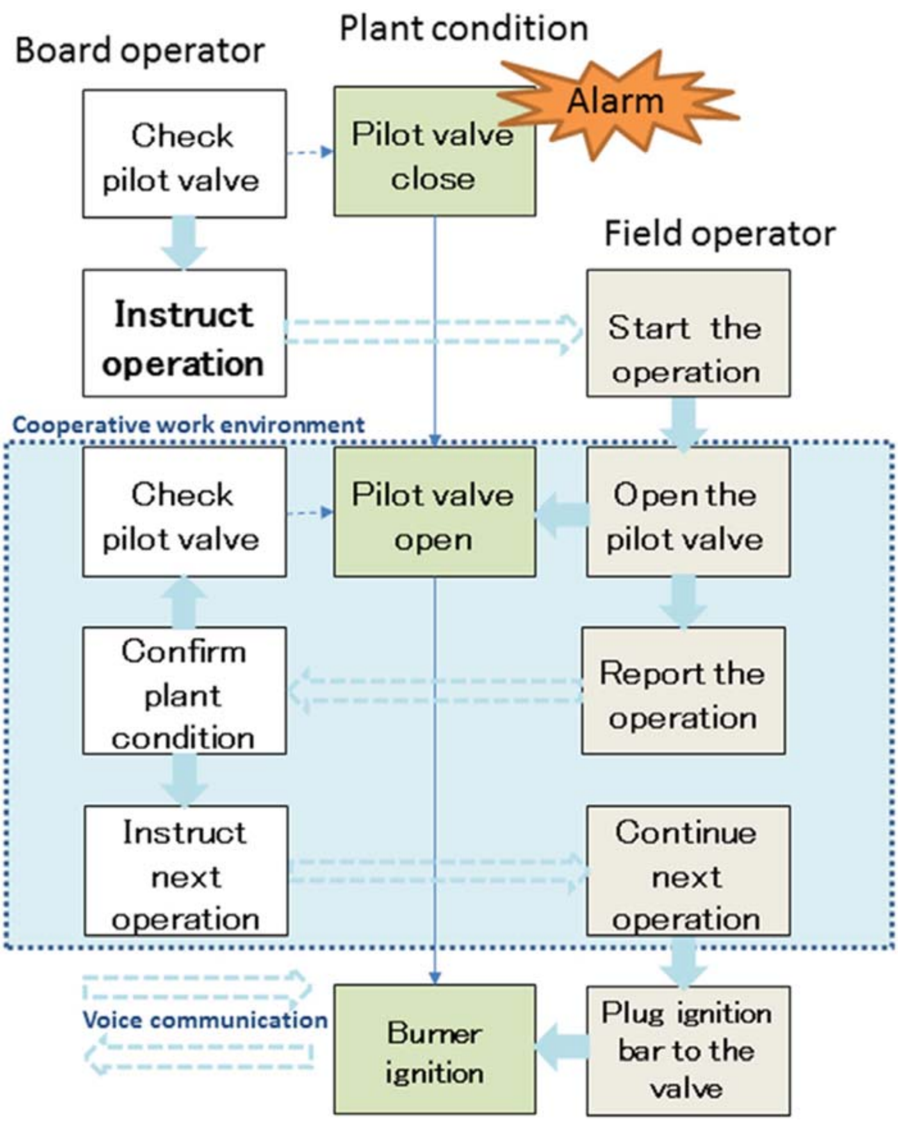

Figure 5.4 The cooperative work environment created by the information-sharing system

5.3 Information-sharing system

5.3.1 Outline of the instructional information-sharing system

The proposed system adopts an operator/server system that consists of a web server and multiple operator PCs (see Figure 5.1). The web server and working devices are connected using the local area network. The operators can refer to the web server information using their tablet PCs or control room PCs. A dynamic plant simulator also runs on the same network, and a web application controls the behavior of the simulator. The plant information about operating procedures is stored in the database to help support the operators. The field operators can confirm the procedures/P&ID and recognize the target facility by using the system to share real-time images through their camera-equipped tablet PCs. This web server can relay information stored in the database, sensor data acquired from the simulator, and onsite real-time images to the board operators' PCs. The functions of this system are as follows.

- Select corresponding work site and display of basic plant information such as piping diagram
- Display current information of the plant (pressure, temperature etc.) in real time
- Messaging; board/field operators can send short text message and reply using the Yes/No button
- Sharing real time field work image

The following usage technique is adopted this system as an information communication technology. In Figure 5.5 shows the flow of information from the dynamic simulator to client PCs. Board operator and field operator can share information via web server in Figure 5.6.

▪ Long polling

A technology that does not immediately respond to a request from a client (browser) but returns a response at a necessary timing. It is used as a pseudo push delivery. For example, return the response at the timing when the text message is updated.

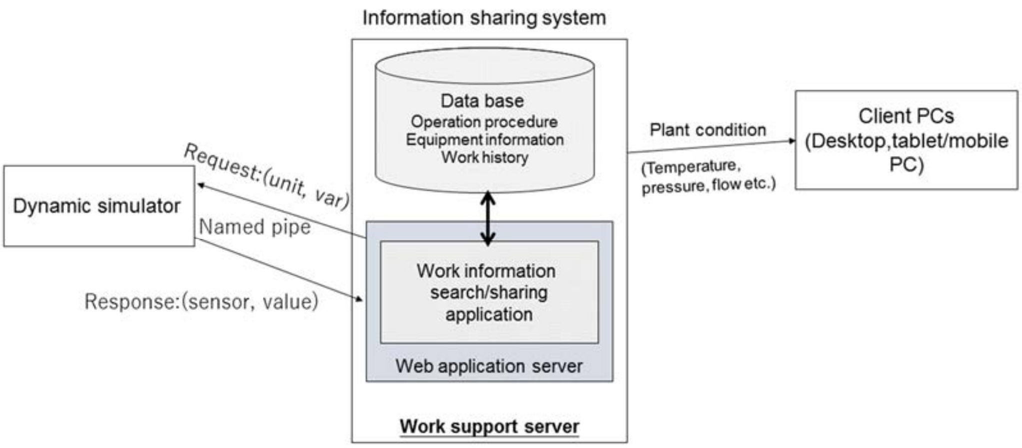

Figure 5.5 The flow of information from the dynamic simulator to client PCs

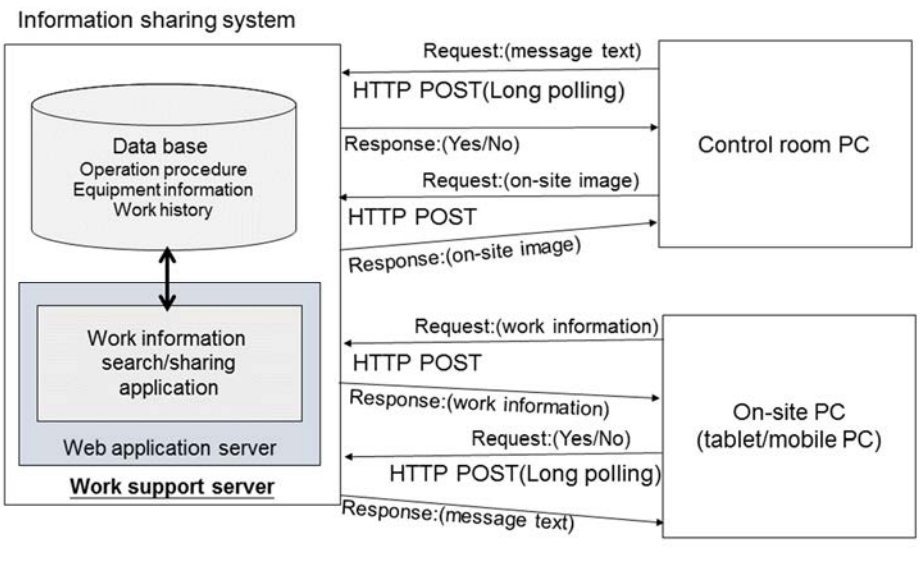

Figure 5.6 The flow of information between control PC and on-site PC

5.3.2 Clarification of role sharing in operating procedures

Actual work in chemical plants is made up of cooperative work via role sharing. In many cases, standard operating procedures (SOPs) are used to enable efficient work. SOPs are displayed in the form of a list on paper, and they usually lack descriptions of operational targets and their location aided through photographs or figures. Further, who is responsible for what operation is usually not clearly stated [88]. In order to work safely, all employees must definitively know what tasks they must perform. To address this, the present system standardized work procedures and created two role-sharing models (one for field operators and one for board operators). The chemical plant conditions depend on human activity - clarifying the relationship between people and equipment helps operators to recognize the real time situations in facilities. The contents of the procedure were divided into steps to systematize the operating procedures; by doing this, the relationship between operators and equipment became clear [88]. This study used a malfunction scenario to create a system for responding to feed trouble with the vacuum gas oil (VGO); the simulation can be used for safety training via the dynamic plant simulator. Standard troubleshooting procedures are shown in the corresponding operation manual of the plant simulator. In the control room, the liquid level of the tank (D 401) drops, and the low liquid alarm (liquid level gauge: LC 401) goes off in the control room due to the stoppage of the supply through the reduced pressure; this causes the LCV 401 (the liquid level control valve) to fully open. When the supply of raw material is stopped, the tank (D 401) becomes empty and the temperature of the heating furnace rises. As a troubleshooting operation, the field operator performs an opening/closing operation of the hand-operated valves in order to switch the circulation system. If the operator mistakes a different valve for the proper one, a serious accident by overheating the heating furnace could occur. Standard troubleshooting procedures are shown as a list. But the information about work sharing for each procedure and the places of equipment are not shown clearly. Although field operations should perform in cooperation with control room operations, operational responsibility in cooperative work is not described enough.

The lack of information regarding trouble shooting procedure was investigated, divided it into 6 time-series steps in this case. An event is defined by subdividing one step by role sharing of work. The event proceeds when the work responsibility moves or the operation target device changes. We complemented the information required to clarify the work procedure and make it systematized, then we sorted the information using the 6w 2 h method. 6w refers to "what", "who", "when", "where", "whom" and "why"; 2 h refers to "how" and "how many" [88]. There is only one operation target device for each event. In case there is no target device in the event, it indicates the communication operation between the operators. Each event and sequence relation is indicated with a symbol and a serial number. The operation procedure is stored in the event and conveyed sequentially according to the progress of the operation. Arrows indicate the preceding relationships between events. The flow from the first operation to the last operation is represented by a flow chart [95] and the whole mechanism is referred to as an operation procedure model. When cooperative work is included in the event, it is further divided according to the role of the operators. Each event is expressed with the following (1), where *i* and *j* are the numbers of the operation.

$$E_{ij} \quad (i = 0, \cdots, n \quad j = 0, \cdots, m) \tag{1}$$

When an alarm is activated, it is shown as E_{00}. When j changes from 0 to 1, communication between the operators is made in the changing direction within the same event. That is, the direction of the arrow indicates the direction of $j=1$. Operation responsibility also moves in the direction of the arrow. When *j* changes from 1 to *m*, the operation is performed by the same operator with in the same event. The plant condition is also expressed in the same way, where the symbol is P_{ij}. Different events are coded as follows:

E_{00}: VGO feed trouble and alarm is activated

E_{10}: Board operator instructs field operator to switch circulation systems

E_{11}: Field operator receives the instruction

E_{20}: Field operator opens the valve (HV 811)

E_{30}: Field operator closes the valve (HV 813)

E_{40}: Field operator reports to control room operator after operating the two valves

E_{41}: Board operator checks the plant condition

E_{42}: Board operator checks HV 813

E_{50}: Board operator checks HV 811

E_{60}: Board operator instructs field operator to check distillation column

E_{61}: Field operator receives the instruction

E_{62}: Field operator checks the state of the distillation column

The cooperative operation model that uses role sharing is shown in Figure5.7. E_{20} and E_{30} are subsequent procedures by field operator. In this case, there is a possibility of mistaking the operation target device [95]. After that, if field operator does not check the plant data thoroughly, this mistake may cause an accident. This study found that communication has quite large role in cooperative work. Onsite work is prompted by instructions from the control room. After receiving the report from the site after completing an operation, further instructions are issued. Figure 5.8 illustrates a subsequent operation procedure model. Here, it is assumed that repetition of communication due to work failure or human factors does not occur. In reality, it is expected the communication of operation instructions/confirmation is more complicated. After analyzing the actual work, the functions necessary for reliable operation between board operators and field operators were implemented in the system to support the operators.

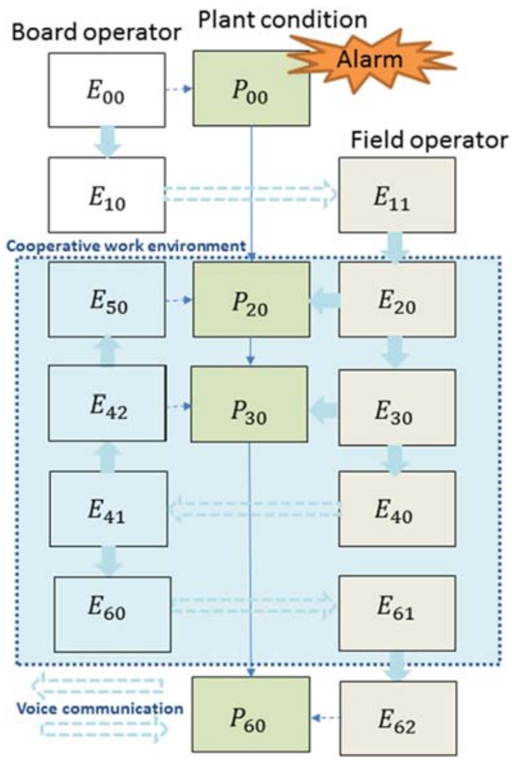

Figure 5.7 Cooperative operation model using role sharing

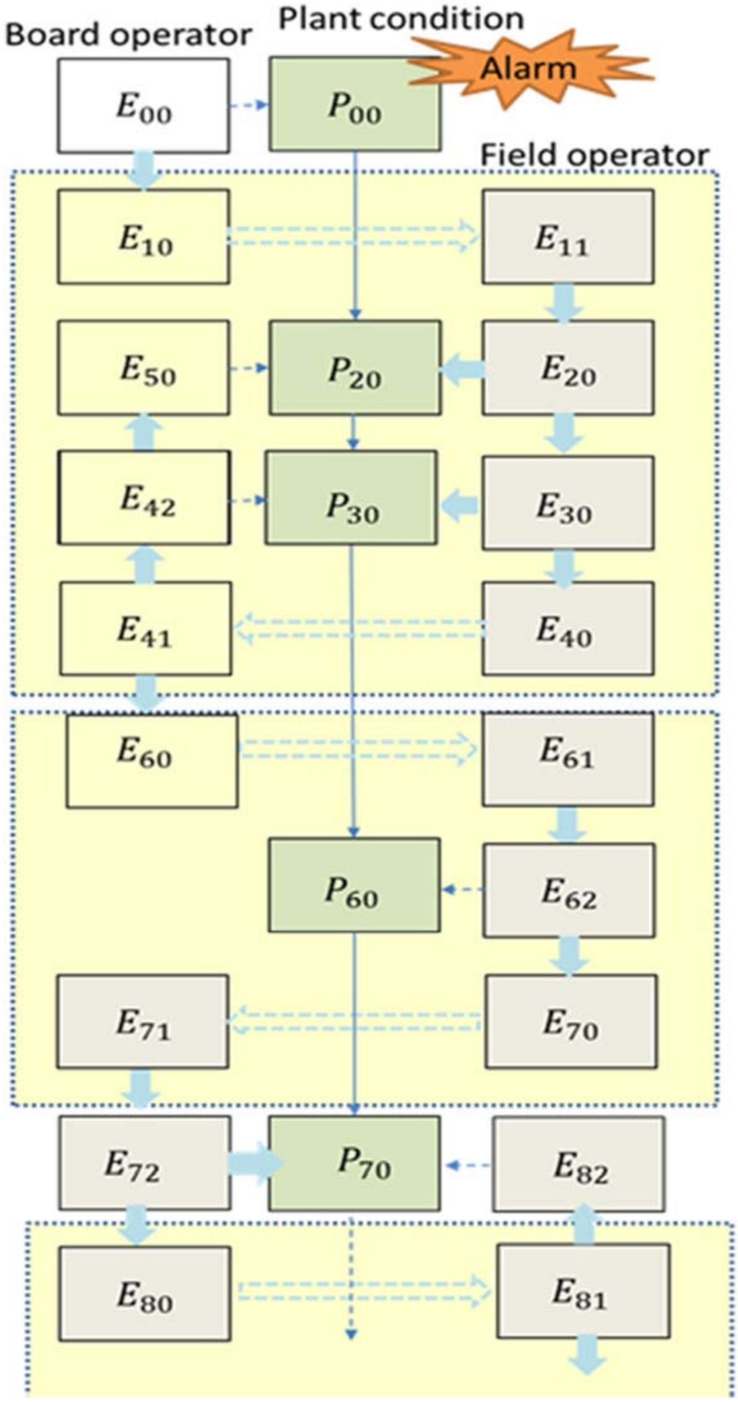

Figure 5.8 Subsequent operation model

5.3.3 Implementation of the proposed system for onsite work

This system can be applied in various situations. By storing a lot of information in the database, various work information can be presented. At the research stage, sensor values from the dynamic simulator are used instead of actual plant data. This system was developed based on the operation procedure for a malfunction, and it was designed to display necessary information (e.g., the workplace, P&ID diagrams, sensor data from the dynamic simulator, etc.) on the operators' PCs. Using the tablet PC's camera, the field operator can send real-time images to the web server to share information with all of the other operators. The onsite workflow (run by the field operators) portion of the information-sharing system comprises the following steps:

1. Check the displayed procedure/workplace/sensor data on the tablet screen
2. Capture real-time images of the target facilities and situation
3. Receive instructional text message and respond using “yes/no” button
4. Operate the target device
5. Check the plant conditions and receive the next work instruction

Instructions and report contents for onsite work change according to time and progress. To prevent miscommunication and misjudgment, moreover, to inhibit inappropriate behavior, the system applies interactive communication using short text messages and a “yes/no” button in addition to voice instructions. Figure 5.9 shows the initial settings and the operation of checking a display; it also shows the PC screen of the control room under operation. The field operators can change the operation information and real-time images. Human errors often occur when a field operator works alone or in a non-steady-state operation [3,11]. Since the proposed system can check the sensor data from the plant simulator in real time onsite, it is expected to be useful for individual work as well.

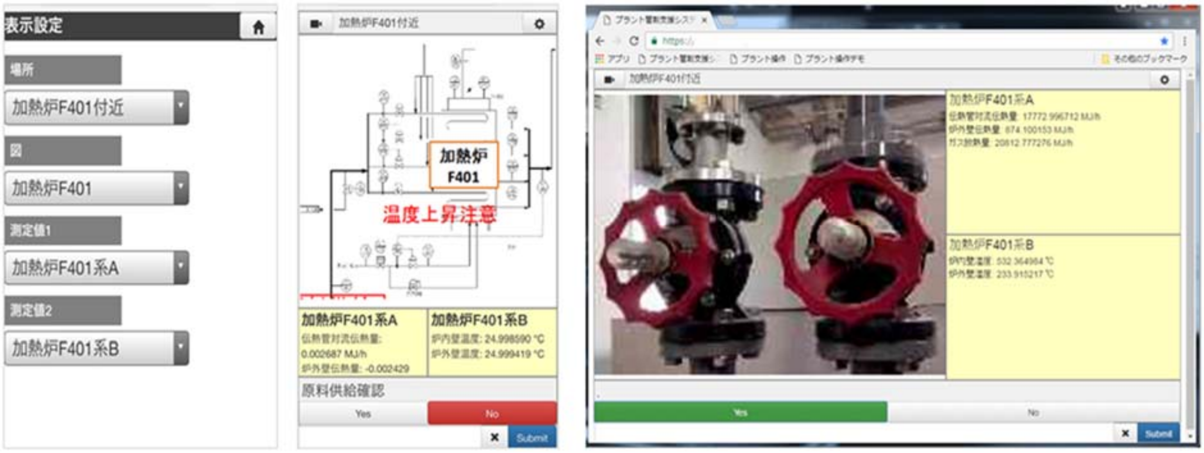

Figure 5.9 Implementation of information-sharing functions

5.4 Operating verification

This system was implemented assuming a malfunction in an operation procedure within the plant simulator. The database for this system stores the information necessary for performing correct work, and field operators can use this system on tablet PC or a small device such as an android smartphone connected to a local area network. Verification experiments were conducted in the laboratory to confirm that the functions implemented in the system were reliable. The main functions of this system are the selection and presentation of operation information, the acquisition and display of sensor data from the dynamic simulator, sharing real-time images, and communication by text message.

5.4.1 Initial setting for using the system

In order to easily bring operation information with them to the site, field operators can use the system via a smartphone or a tablet PC with a camera. This system aims to support both field operators and board operators. Operation information is presented as instructional information from the control room. Field operators can also select the operation information that they would like to check while they are onsite. The initial screen of the system for the

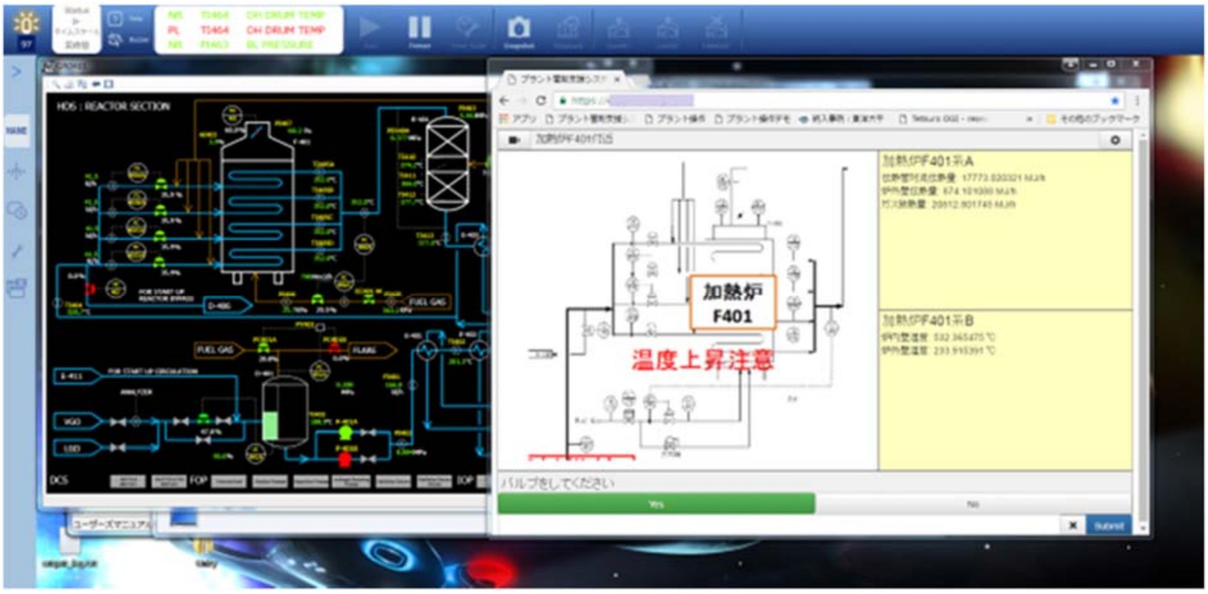

Figure 5.10 Initial screen of the system (for board operators)

board operator side is shown in Figure 5.10. Instructional information is displayed on the tablet PC, with the sensor data information imported from the dynamic simulator displayed on the right side of the screen. The dynamic simulator and the web server of this system are installed on different PCs, and the information to be presented to the operators is selected and displayed. Figure 5.11 shows the corresponding operating experiment for the field operators. If too much information is used, it may cause confusion among the field operators.

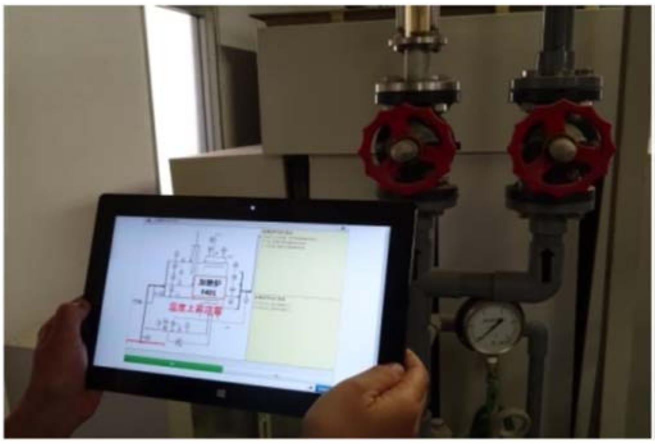

Figure 5.11 Operation experiment (for field operators)

5.4.2 Verification experiments of the information-sharing function

In chemical plants, field operators and board operators work in different places; therefore, board operators cannot see the situation occurring onsite in the control room. In order to reproduce this situation, verification experiments were carried out using facilities located in different places from the laboratory. In order for the system to operate normally, the web server and the tablet PCs must exist on the same network. A dynamic simulator also exists on this network. This system adopted a server/operator system, enabling information to be shared between multiple operators. The verification experiment confirmed that the system can be used to share information among the operators.

Figure 5.12 Sending a real-time image using a tablet PC

Figure 5.12 shows a real-time image captured by tablet PC being sent from the field operator to the control room operator. The information is also being shared with other devices on the same local area network. Figure 5.13 illustrates the information-sharing operation being conducted via a smartphone located in the field.

Figure 5.13 Screenshot of verification experiment of a smartphone

5.5 Conclusion

In this study, an information-sharing system was developed to provide a safe and cooperative work environment for field operators and board operators using a dynamic simulator as a virtual plant. Experiments confirmed that the developed system works as intended. In order to reduce accidents caused by human factors as well as operators' workloads, the following functions were implemented: the selection and presentation of operation information, the acquisition and display of sensor data from the dynamic simulator, sharing real-time images, and communication by text message. There have been rapid generational changes in the workforce in Japan. Skilled workers' techniques and knowledge are being lost, and inherited technology and past accomplishments are essential to enhancing the safety of work environments. Thus, in cases where inexperienced young field workers have forgotten the work procedure, they can help each other by sharing the operation information in the cooperative work environment facilitated by this new system. In the case of an emergency, prompt response operations are required, and hopefully, this system will ensure that onsite response operations can be carried out smoothly. In addition, this system was implemented with the actual controls of a dynamic simulator functioning as a virtual plant, and in the near future, this system can be used for safety training/education using a real onsite work environment.

Chapter 6 Conclusion

Safety management of large-scale industrial plants is a request of our society. So many studies have been done so far to achieve this purpose. In my opinion conventional Japanese safety management methods have the following characteristics. It is a bottom up type safety management system. Safety is guaranteed by "person's efforts", "maintenance" and "improvement" that support the onsite work environment. In addition, we have pursued safety measures (absolute safety) to completely remove danger. There are variations due to human judgment in safety measures that depend on individual different values. Therefore, the safety measures expected at the time of accident or trouble may not function sufficiently.

The idea of securing safety by reducing the risk to an acceptable level is the mainstream in the world. This issue is considered that our society should be adopt this idea. In this study, it is constructed the information flow utilizing computer technology for on-site work support and safe operation. It is expected that this study contributed to the establishment of a mechanism for on-site personnel to convey correct information. As a conclusion this thesis summarized as follows.

Chapter 1 introduced the purpose of this study and the composition of this paper.

Chapter 2 described the background of this study and the previous work related to this paper and showed the position of this thesis.

Chapter 3 is indicated the two main targets to prevent human error from being main cause of accidents in chemical plants.

(1) A technique was proposed that would reorganize the paper format operating procedure manuals from the perspective of preventing human error and would enable standardization for incorporation on computer systems.

(2) An image recognition technique was proposed that would enable the confirmation of operating targets without using the machinery of special assistance such as AR markers. The background of the operating target installation area and the positional relationship with other machinery were used for confirming the technique.

(3) By incorporating the two techniques into a computer system, an information display system for plant operations was developed and system performance was verified through the application of examples.

Chapter 4 explains a system to provide instructional information for field operators by using AR and image recognition technology for chemical plants. By using these technologies, this system has made it possible to accurately recognize target equipment. The operator can recognize target equipment/area with the help of a camera-equipped tablet PC using AR marker or using image recognition technology of the system. The field operators can detect the correct equipment to perform procedures on and more easily differentiate between similar aggregating equipment, such as pipes and valves. Thus, the system can reduce the risk of serious accidents caused due to operators mistaking the device to be operated. After the procedure is completed, the next procedure is displayed by updating plant information. The number of equipment operated by the field operator is managed by the board operator in the control room. In addition to presenting detailed plant information, the function of this system should expand to include presenting instructions to board operators as well. In future, this system can be implemented with the actual controls and systems, and by using real plant data. Inherited technology and past accomplishments are essential factors in enhancing competitive production. The information on this report can use for risk communication and risk management. The proposed system takes down the issue of human error by recognizing correct equipment, presenting relevant information, and having a confirmation function to prevent erroneous operation.

In Chapter 5, it is explained that an information-sharing system was developed to provide a safe and cooperative work environment for field operators and board operators using a dynamic simulator as a virtual plant. Experiments confirmed that the developed system works as intended. In order to reduce accidents caused by human factors as well as operators' workloads, the following functions were implemented: the selection and presentation of operation information, the acquisition and display of sensor data from the dynamic simulator, sharing real-time images, and communication by text message. There have been rapid generational changes in the workforce in Japan. Skilled workers' techniques and knowledge are being lost, and inherited technology and past accomplishments are essential to enhancing the safety of work environments. Thus, in cases where inexperienced young field workers have forgotten the work procedure, they can help each other by sharing the operation information in the cooperative work environment facilitated by this new system. In the case of an emergency, prompt response operations are required, and hopefully, this system will ensure that onsite response operations can be carried out smoothly. In addition, this system was implemented with the actual controls of a dynamic simulator functioning as a virtual plant, and in the near future, this system can be used for safety training/education using a real onsite work environment.

In order to prevent an escalation of the accidents, the correct operation must be performed without any human error. The proposed systems can support operators achieve this level of accuracy. Furthermore, the system can also be used for safety education and training for young plant operator. The proposed systems are expected to aid the next generation of operators in the field and also help clarify non-steady-state operations.

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