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Augmented Reality for Maintenance Operator for Problem Inspections

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***Abstract*—**Current production-oriented factories need maintenance operators to work in shifts monitoring and inspecting complex systems and different equipment in the situation of mechanical breakdown. Augmented reality (AR) is an emerging technology that embeds data into the environment for situation awareness to help maintenance operators make decisions and solve problems. An application was designed to identify the problem of steam generators and inspection centrifugal pumps. The objective of this research was to find the best medium of AR and type of problem solving strategies among analogy, focal object method and mean-ends analysis. Two scenarios of inspecting leakage were temperature and vibration. Two experiments were used in usability evaluation and future innovation, which included decision-making process and problem-solving strategy. This study found that maintenance operators prefer build-in magnifier to zoom the components (55.6%), 3D exploded view to track the problem parts (50%), and line chart to find the alter data or information (61.1%). There is a significant difference in the use of analogy (44.4%), focal objects (38.9%) and mean-ends strategy (16.7%). The marked differences between maintainers and operators are of the application of a problem solving strategy. However, future work should explore multimedia information retrieval which supports maintenance operators for decision-making.

***Keywords*—**Augmented reality, situation awareness, decision-making, problem-solving.

I. Introduction

A. History

AR is the evaluation of virtual reality which interacts not only with the virtual environment but also physical world [1]. Normally, people prefer to apply superposition of text, image, animation and 3D objects into the real environment seamlessly with a computer-generated system [2] which brings users into the immersive experience as if it is real. The first augmentation was created by using real photos presented by CAD software, with the evaluation of manual alignment. AR has already been applied in the industrial field, such as production design, manufacturing, commissioning and inspection [3]. Mobile augmented reality (MAR) tracks the information from the environment without changing the outlook of the product [4], and inserts the function into a specific field [5], and AR enables maintenance operators to process real-world tasks [1].

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B. Background

Cognitive processing includes perception, memory, categorization and problem-solving, and as well helps maintenance operators in modeling the multi-attribute decision-making [6]. Situation awareness combined with augmented reality supports maintenance operators on ontology-based context-awareness, which is used to aggregate and process the data [7], [8]. AR has a potential to help users to improve on the accuracy of information and reduce human errors, also provides suggestions for maintenance operators to make decisions [9] such as positive notification; in addition, AR provides information classification for users to collaborate with each other for problem-solving [10].

C. Condition

In a production-oriented factory, maintenance operators have to work in three shifts every day. For the intermediate workers, maintainers and operators collaborate with each other to maintain and operate complex systems and equipment. The pump is important to transfer energy between different units in the factory. If a pump does not operate well, the system might breakdown without solving the problem in time. The centrifugal pump is common in the heat recovery project, which includes Heat-recovery coke oven (HRCO) and Heat-recovery steam generator (HRSG) parts (Fig. 1). According to the technical regulation, maintenance operators have to follow the maintenance and operating procedure. They need to recognize the situation by user experience, reason the cause of the problem with plenty of knowledge and find the appropriate strategy for problem inspection.

Fig. 1 Clean-type heat recovery steam generator project (HRSG)

D. Problem Statement

In general, maintenance operators often make knowledge-based mistakes and misinterpretations during pump inspection.

In order to control the system or equipment, the knowledge is needed such as equipment structure and pipeline layout, maintenance and operating procedure, breakdown prevention and troubleshooting. The deficiencies or failures will be occurring at the planning stage if they lack the knowledge. In order to perceive the environment and comprehend the situation, experts prefer to inspect and detect the problem by multiple sensory, such as hearing and visual, inspection. But novices and intermediates lack this kind of experience. They have a limitation of decision making criteria and are prone to mistakes.

E. Research Questions

For this study, it aims to understand how well maintenance operators utilize AR in detecting and inspecting the problems at the centrifugal pump.

1) How does AR medium help the maintainers and the operators in making a decision through reasoning the cause of the problem?
2) What kind of AR medium will efficiently assist maintenance operators in inspecting the leakage, temperature and vibration of the centrifugal pump problem?
3) Which problem-solving strategy will the maintainers and the operators choose after using AR, such as analogy, focal objects method and mean-ends analysis?

Maintainer and operator allowed taking a different decision-making processes and problem-solving strategies during task performance. Chinese maintenance operators are the subjects for inspecting the circulating water pump.

II. Literature Review

The cognitive processing increases when users interact with AR [11] in terms of situation awareness, decision-making processes, and problem-solving strategies. AR assists users in recognizing their surroundings through controlling the position, scale and orientation, and analyzing between the virtual and the real objects in selecting the annotated information [12]. Hou *et al.* [9] said that AR facilitating on piping assembly with 2D drawings is productive, accurate and improved performance. It could reduce cognitive workload.

Two methods for information processing are 1) a context-aware assistance system used for the real-time information exchange with an AR environment, providing the communication platform with the indoor localization for the maintainers [8]. 2) AR-MS (Augmented Reality Multiscreen) system used to keep crucial information and reduce the discussion complexity, as well as the data query, problem prediction and decision-making during the discussion [13].

AR embedded in a portable game console with a certain size display, has compared the correlation among situation awareness, presence and performance. Situation awareness increased a positive correlation with the current information. AR enhanced the situation awareness and significantly improves the user performance and decision-making [14]. It guides the analysis of a situation for problem-solving and finds the solution for troubleshooting. The application of AR medium transfers the situation into the information and data for the maintenance operator in inspecting the equipment or system.

AR is a supplementary for users understanding and considering the cognitive psychology knowledge such as information process. It prevents mistakes and improves user experience and performance [15]. Furthermore, it presents the relationship between environmental stimulation and sensory experience [7]. The drawback is it is just the pure theory without experiment to verify the perspective.

The maintenance operators can detect some clues from the problem situation by AR medium representation. They are able to give reasons and make inference on the situation for the future breakdown, according to the level of emergency and serious situation. The maintenance operators create a to-do list in their mind and set the priorities, troubleshoot the specifications or parameters standards.

An immersive scenario was setup to recall the memory of real scenes. Maintenance operators combined personal knowledge with AR as of interactive application. The AR experiments were verified to determine the performance of decision-making processing and problem-solving strategies.

Though the literature review does not have integrated viewpoints and appropriated inferences, and evidence to support the idea of problem inspection. Graphic visualization and knowledge will be used as a guidance to the experimental methods in the research.

III. Methodology

A. Task Performance

The purpose of the experiments was to examine how AR helps maintenance operators identify the problem and investigation. These experiments include the information process situation awareness, decision-making, problem-solving, and recognition.

Experiment 1 is the problem-solving strategy that reflects the strategy selection, and evaluation for the interface and interaction performance. Participants were asked to read a scenario about the pump's problem, among them leakage, high temperature and violent vibration. Then they assigned the task to draw a picture of the pump that they wished to inspect before testing. In order to identify the problem, participants compare and choose the best AR medium types that help them identify the problem.

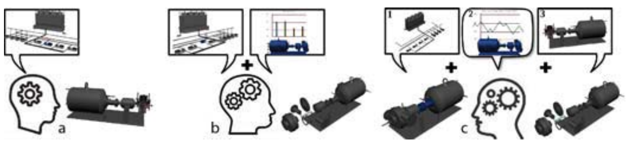

Fig. 2 Problem-solving strategies

The process was taped on how participants walk through the AR situation. They were asked which strategy was used to solve problems (Fig. 2) and provide feedback on the quality of the interface.

Three conditions of the problem-solving strategies:

a) If subjects interpret the meaning directly from AR to solution (the AR with solution), they used the method of analogy.

b) If participants interpret the meaning differently from what the AR presents and it leads to another solution. It means that they used method for focal object.

c) If subjects used mental model on how to solve the problem similar to the process, it means they used the method of mean-end analysis.

Experiment 2 takes the decision-making processing to reflect the difference of information process between maintainers and operators by the preferred AR medium. It also verifies the effectiveness of AR for the maintenance operator and problem inspection.

TABLE I
AR MEDIUM TYPE

Leakage	Vibration	Temperature
Highlight problem part (complexity reap)	3D section view (occultation)	Line chart (measurement)
Alert of leakage point (out-of-loop syndrome)	3D exploded view (dis-assembly)	Gauge chart (different colors)
Zoom out problem part (misplaced salience)	3D model (rotation and zoom)	Bar (interactive) chart (group)

Testing the AR medium is carried out in three sets (Table I), leakage group, temperature and vibration group, and asking participants to select the most preferred medium. The test monitor analyzes the statistic results and participants' feedback. According to occurrence of failure frequency, pre-setting bearing temperature below 65 °C and vibration under 0.06 mm is the most common problem caused by pump leakage. The problem (Fig. 3) may be the damaged seal or improper installation.

B. Tools and Environment Setting

IPhone 6S was selected as a portable device which displays AR medium. Tian-Yan AR software is a back-end web platform. The medium types include text, image, and (AR) video and 3D model. The smartphone automatically uploads the information from the Internet. The target object was scanned through the mobile phone camera and the 3D model or animation will pop up on the interface. Participants can do the real-time inspection (Fig. 4) with the tools that helps them make decisions. The testing environment is in integrated pump house (Fig. 5). The test monitor explains the task that participants need to complete and observes by taking notes.

C. Population and Demographic

The participants (Table II) were selected from clear-type heat recovery coke oven project (HRCO) and clear-type heat recovery steam generator project (HRSG). They have vast experience in operations and maintenance of over three years. The subjects will consist of 18 people who have different working experience between maintenance and operation.

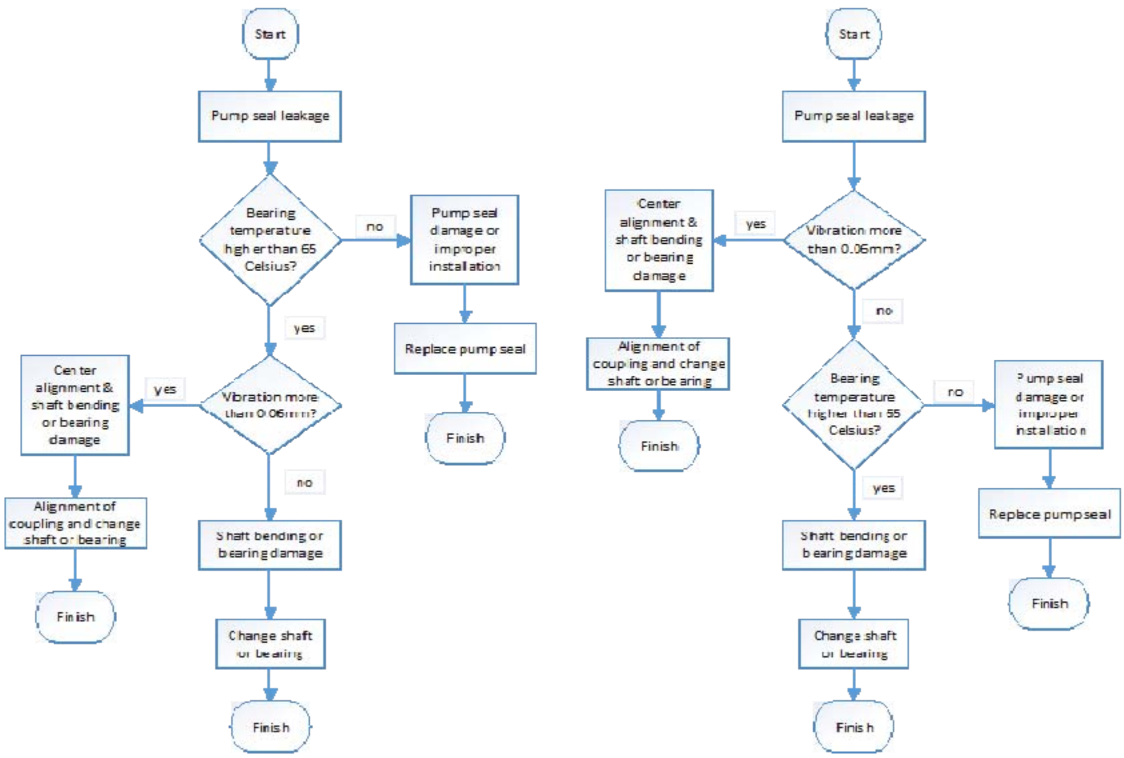

Fig. 3 Sequence of decision-making and problem-solving

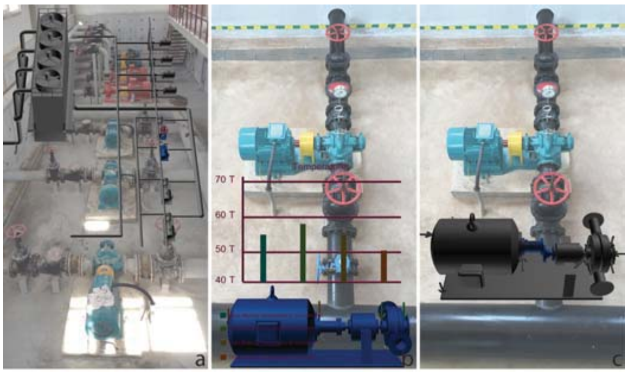

Fig. 4 Interface design

Fig. 5 Integrated pump house and pump test

TABLE II
GENERAL INFORMATION

Characteristic	Range	Frequency distribution
Position	Maintainer, Operator.	Maintainer 6 persons; Operator 12 persons.
Education	Technical school; Middle school; College/university	Technical school 8 persons; Middle school 2 persons; College/university 8 persons.
Working age	Over 3 years' experience	2-5 years with 1 person; 6-15 years with 8 persons; Over 15 years 9 persons.
Experience	Coal & coke plant; Power plant	28 % in coal & coke unit; 5 % in maintenance unit; 11% in thermal control unit; 11% in boiler unit; 11% in desulfurization unit; 6% in water treatment unit; 11% in steam turbine unit; 17% in electric unit.

IV. RESULTS

The results of the data come from the sample size of 18 subjects. The questionnaire included three parts: general information, decision-making process and problem-solving strategy. In order to verify the AR application, the usability testing is divided into five aspects:

1) Problem-solving strategy selection.
2) Evaluation of the interface and interaction.
3) Preferred AR medium selection.
4) Decision-making processes selection.
5) Effectiveness of AR.

SPSS statistics are used to analyze the data collected from the subjects and descriptive analysis. The comparison of the means includes one-sample t-test and an independent sample t-test.

A. Problem-Solving Strategy

The independent sample t-test was used to find out which strategy that maintenance operators used. The bar chart (Fig. 6) presents the difference between operators and maintainers who used AR on problem-solving strategy. An average number of strategy selections from the operators (M=1. 41, SD=0. 66) is less than the maintainers (M=2. 33, SD=0. 51). There is a significant difference, at (16) =2. 93, p=0. 01. The operators preferred to use analogies, and maintainers used the focal-objects method compared with mean-ends analysis. Only operators selected the analogy strategy which accounts for 44.4% of the subjects. Both maintainers and operators chose focal-objects methods which accounts for 38.9% of the participants. In summary, the analogy strategy is slightly more popular than the focal-objects method.

Operators are responsible for monitoring the distributed control system. They can track the information at the initial observation, and therefore, the operators use the analogy the most. Maintainers work on troubleshooting when there is equipment malfunction. They disassemble the equipment and search for clues to the problem. As a result, maintainers prefer to use the focal-objects method. During the routine inspection of working condition, operating and maintenance procedure of the guidebook are used for mean-ends analysis. Maintenance operators used their mental model to reach the goal step by step using with their experience. This cause comes from the knowledge-based mistake that leads to the failures in judgmental and inferential processes.

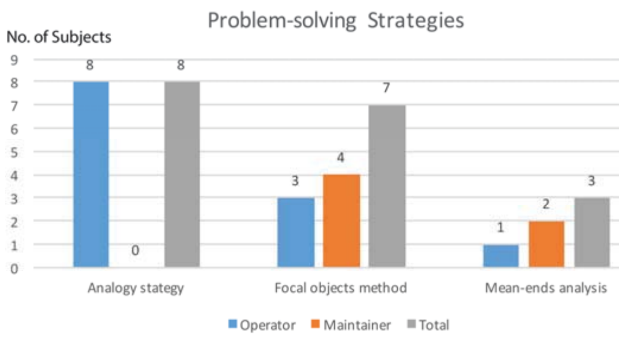

Fig. 6 Problem-solving strategies selection

The selection of the problem-solving strategies (Fig. 7) is based on different reasons. For the analogy, the subjects' selection is from the intermediate maintenance operators. Nearly all of them had more than six years working experience, so they preferred to use previous experience as a method for problem-solving. For the focal-objects method,

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they could find the problem clues in the situation and synthesize the concepts to solve the problem. For the mean-ends analysis, maintenance operators use the mental model of the maintaining procedure to detect the problem. They set the final goal which relies on the information supported by the theoretical perspectives and reach the goal through a sub-goal.

Fig. 7 Reasons for problem-solving strategy selection

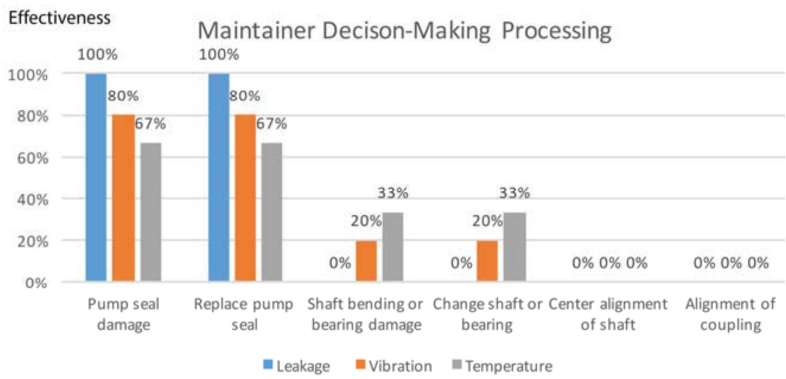

Fig. 8 Maintainer decision-making processing

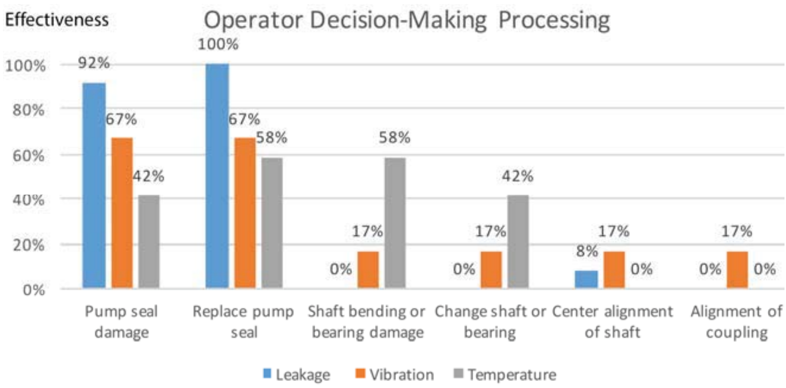

Fig. 9 Operator decision-making processing

B. Evaluation for User Interface and Possibility to Act

The evaluations for interface and interaction take descriptive method to analyze the results. The majority of maintenance operators (94%) think that the AR medium has a positive influence on problem inspection. An operator in a coal and coke unit considers the AR medium as being difficult to track and scan at a long distance for larger equipment and systems. Half of the participants (50%) believe that the AR represents appropriate data and contains the essential information that supports equipment inspection. While 27.7% of maintainers consider that they need more information, such as equipment specification, the operators think that the information is rationale for monitoring.

The maintenance operators believed that AR is clear and easy to understand during the problem inspection. Over half of the maintenance operators believe that the performance of AR was only just slightly misunderstood. The reason is the pattern of AR medium selected in the performance. Half of the subjects feel that they can prevent the breakdown through the inspection of the severity of the situation by using the AR medium, while 22.3% participants think they can deal with a few things, and 27.7% believe they can strongly control the situation before it worsens. According to the trend, maintenance operators maintain the status and control the problems to prevent them from escalating via the information supported by the AR medium.

C. AR Medium

The AR medium pattern is analyzed with descriptive statistics. The maintenance operators faced three different kinds of AR medium, leakage pattern, vibration pattern and temperature pattern. Comparing the three types of AR medium, animation, 3D model and 2D image, eight participants (45%) prefer animation for situation representation and decision-making. The difference between them is not quite significant. The reason is that animation could present not only a 2D image but also a 3D model.

For the detection of a problem component via an image, 10 subjects (55%) prefer to zoom out the problem component which takes more than half of the population. While five subjects (28%) like the signal alert given by the distributed control system (DCS). Maintenance operators prefer to get the detail of the problem part. The magnifier function decreases human errors of slip or lapse. For vibration inspection via equipment construction checking, nine maintenance operators (50%) prefer to use the 3D exploded view, while six participants (33%) chose to use the 3D section view to check the internal structure. Maintenance operators would easily get the information of what they want through rotation, zoom in/out. For temperature monitoring via video, nearly two thirds of the subjects (61%) chose the line chart to represent the value changes over time. The timeline was used to check history record and compare the difference to the past value. AR is able to help them in terms of a real-time check of temperature and history records.

D. Decision-Making Processing

Fig. 8 shows the maintainer's decision-making processing. The majority of participants (80%) insist that the problem is caused by a seal leakage, which was the result of damage to the seal damage or because of improper installation. Only 20% of participants considered that they need to check temperature. And just 7% (33% of those who checked the temperature) believed the source of the problem was from high temperature, shaft bending or bearing damage, and should change shaft or bearing. While 13% (67% of those who checked the temperature) believe that the problem comes from leakage. After analyzing the temperature, nobody considers that the problem came from vibration. In total, 93% of maintainers believe the problem originated from leakage which needed replacement of the pump seal. Only 7% of maintainers think the problem came from high temperature which required a change of shaft or bearing. If a maintainer found the correct cause of the problem, they could put forward the appropriate solution for that problem.

Fig. 9 presents the operators' decision-making process. A total of 67% of the subjects insisted that the problem was caused by a seal leakage. Thus, the solution was to replace pump seal. While 17% of the subjects considered that they need to check the pump vibration. None of the subjects supported the notion that the problem emanated from vibration after inspection. Only 17% of the subjects considered that the temperature required checking, while 17% thought that there was a need to change the shaft or bearing because of high temperature. Another 17% believe the problem emanated from leakage after checking the temperature in rational range. In total, 83% of the subjects believe that the problem came from the pump seal leakage. Some 17% of the subjects believe that the problem originated from high temperature which causes shaft bending or bearing damage, so they needed to change the shaft or bearing. After reasoning and extrapolation, 17% of the operators could go back, trace the correct site of the leakage, and offer the appropriate solution for the problem.

In summary, 90% (16 people) of the participants believe that the problem was pump seal leakage, and 10% (2 people) of participants thought the problem came from high temperature. Comparing the operators and maintainers in two information processing methods, maintainers select the most convenient method (leakage-temperature-vibration) to understand the situation, find the cause of the problem and make the decision.

According to the two different decision-making processes, 10 participants used the analogy strategy. Three participants used the focal-objects method, and five participants used mean-ends analysis.

1) For the analogy strategy, 10 participants directly from the AR medium were aware that the problem was coming from the pump seal leakage. The reason was pump seal damage or improper installation. The suggested solution is to replace the pump seal.
2) For the Focal-objects method, a participant detects the clues from the leakage problem, and then checks the temperature to see whether it was over the upper limit (60 ºC). Two participants understand the leakage situation with vibration features (0.06 mm).
3) For the mean-ends analysis, three participants used the mental model to check the leakage problem; they then inspected the temperature to establish whether it was high or normal. Verification of the vibration is in the normal range. Two participants set the sub-goals to inspect the leakage problem, and then check vibration to see whether it was within the reasonable limits. Finally, they went ahead to inspect the temperature.

E. Usability of AR

One sample t-test was used to identify the ease to use AR. The evaluation of AR applied in the production field between the operators and maintainers. The opinion or attitude of the maintenance operators on ease to use and usefulness of AR has been described below. The average satisfaction of ease to use ($M=3.66$) was significantly higher compared to the norm ($M=3$), $t(17)=2.915$, $p=0.01$. The effect of size was medium, $p<=0.05$, $d=0.66$. Most maintainers and operators (61.1%) believed the AR medium was easy to use and useful. Only two operators (11.1%) from the coal and coke unit consider AR difficult to use. This is because the AR medium is capable at short distance from the mobile camera without massive equipment and systems, such as coke oven and transmission belts. In conclusion, AR is easy to use for maintenance operators and useful in decision-making.

V. Conclusion

A. Situation Awareness

AR within rational medium is useful for maintenance operators in term of investigation and interpretation. Animation assists the maintenance operators on the perception of the environment [9]. Because of the characteristics of continuity and intuition, AR could reduce the cognitive workload. The magnifier, 3D exploded view and line chart is the most preferred medium in each AR pattern group. AR aids in comprehension of the situation from problem identification and interpretation through to portable device, so that maintenance operators can understand a situation clearly and inspect without human error. Well-organized information and data help the maintenance operators avoid knowledge-based mistakes.

B. AR Performance

Enhanced understandings of AR help maintenance operators make a decision for best performance, reduce misinterpretations of the situation, and manipulate what they observed [14]. The failures might be occurring without the judgmental and inferential processes. The AR medium makes it easy for maintenance operators to use in situation awareness, decision-making and problem-solving. Maintenance operators can make an appropriate decision for efficient and effective problem-solving [13].

C. Decision-making and Problem-solving

The maintainers and operators identify the intention with different approaches, in order to process the information via AR. According to the routine inspection, the mental model of operators goes through situation analysis, component structure, data and information. Compared with the operators for troubleshooting, the maintainers have more perceptual sensitivity to find a simple procedure for decision-making. Moreover, they have more knowledge about the decision criteria to synthesize the clues. Their working habits can also affect the decision-making process, while AR helps operators to make the correct choices. As a result, AR with perception mechanisms in a complex system could assist maintenance operators to make the appropriate decision [16].

Maintainers and operators have different preferences when applying problem-solving strategies in the decision-making process. AR provides data and information for maintenance operators to solve the problem and carry out the multi-attribute judgment [6]. The operators prefer to use the analogy strategy to create awareness and detect the problematic situation, because of previous working experience. The maintainers prefer to use the focal-objects method to reason the cause of the problem, and analyze the scenario in order to choose a solution. AR helps the maintenance operators to find perceptual information in the problem scenario, and use the appropriate problem-solving strategies for task performance.

D. Design Problems

Users have different kinds of working experience which are difficult to classify and compare. Some of them have both maintenance and operation experience, and so the position was divided with two factors in the user research. Working years reflect how much knowledge they have learned, and performance reflects the application of knowledge. Maintenance operators have different methods of recognition on the 3D components. The subjects were allowed to ask the name of components during testing. Because of the limitation of skills and technology, some user requirements are difficult to carry out using this AR software. A balance between technology and user requirements could be designed for real products. Completion and performance time are measured as indicators for productivity [9]. It is difficult to count the performance time during the usability testing, because some of subjects chose to explain the experience about the theory and practice to the test monitor during testing. A questionnaire and video recording was used to measure the action of the performance.

E. Research Contribution

Maintenance operators understand the situation by using an appropriate AR that can eliminate misinterpretation. In multi-tasking, maintenance operators use different methods and tasks. Magnifier function with occultation help them zooming into a selected area for problem inspection, and avoid knowledge-based mistakes. During application of the 3D exploded view in the structure inspection, the internal part of the equipment and system will represent the situation for troubleshooting. Line chart for information monitoring, data change and history record are used to monitor and compare the results during operation and maintenance.

The appropriate AR medium helps maintenance operators during problem inspection. For the interface evaluation, during routine checking of the equipment, accurate information can easily be accessed through the portable device. For the performance evaluation, when maintenance operators are in trouble during an emergency, useful data can be monitored and the system adjusted to establish a safety situation.

In decision-making processing, the maintainers have high efficiency on perception and performance. They combine situation clues (perceptual sensitivity) with maintenance experience (decision criteria) to make the right decision. AR fits in different maintenance situations, such as time-based maintenance (TBM) and condition-based maintenance (CBM). Operators are limited by the working procedure requirement and their information operating experience. However, the majority of operators can avoid knowledge-based mistakes during the inspection of the problem situation. AR suits different operation situations such as troubleshooting and equipment testing.

Problem-solving strategies used in AR help maintainers improve working efficiency. Maintainers can use the application to recognize equipment structure with the 3D exploded view. They apply the focal-objects method to check component specifications and match maintenance tools to repair or change faulty parts. Problem-solving strategies used in AR help operators improve operating accuracy. Operators use the application to identify system status, apply analogy strategy to monitor and detect the information and data, and remote communication with colleagues for application-supported cooperative work for situation awareness.

F. Future Work

The results of this research could be launched in the AR application for improvement and innovation. This is because AR presents an ease to use for the operator and maintainer, and is useful for problem inspection situations. The portable device embeds preferred AR medium in the design with the required interface and interaction, and is set into two different accesses for maintainers and operators, because of the different focuses on decision-making processing and problem-solving strategy. The product could be used in the routine operation and maintenance using multimedia information. The work procedure during multi-tasking for operators and maintainers includes checking, operating, maintenance and recording. It could be used for remote-collaboration.

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