International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:10, No:10, 2016

Portable Hands-Free Process Assistant for Gas Turbine Maintenance

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***Abstract*—**This paper presents how smart glasses and voice commands can be used for improving the maintenance process of industrial gas turbines. It presents the process of inspecting a gas turbine's combustion chamber and how it is currently performed using a set of paper-based documents. In order to improve this process, a portable hands-free process assistance system has been conceived. In the following, it will be presented how the approach of user-centered design and the method of paper prototyping have been successfully applied in order to design a user interface and a corresponding workflow model that describes the possible interaction patterns between the user and the interface. The presented evaluation of these results suggests that the assistance system could help the user by rendering multiple manual activities obsolete, thus allowing him to work hands-free and to save time for generating protocols.

***Keywords*—**Paper prototyping, smart glasses, turbine maintenance, user centered design.

I. Introduction

THIS paper presents a solution for supporting the process of maintaining gas turbines. The fundamental structure of a gas turbine consists of an upstream compressor, a combustion chamber, and a downstream turbine. After being compressed air enters the combustion chamber where inflammable gas is inserted and ignited. Hot air is then pressed through the turbine, making it turn, thus producing electricity.

The most common problems with gas turbines are damaged turbine blades and damaged heat tiles. Turbine blades occur in the upstream compressor and in the downstream turbine. Turbine blades in the compressor can be damaged when undesired objects (e.g. small animals or waste) are being sucked in by the air upstream. Turbine blades in the downstream turbine can be damaged by parts of damaged heat tiles or screws. Heat tiles are ceramic panels that cover the combustion chamber's interior walls. Since the outer hull of a gas turbine is made of metal and since the temperature in the combustion chamber can be higher than what the metal hull can support, the heat tiles are needed for protecting the outer hull. Actually, the temperature can get so high that it damages even the ceramic tiles over time resulting in cracks and sometimes even in tiles breaking into parts. This must be avoided at (almost) all cost since such parts can heavily damage turbines blades that represent the most expensive parts in a gas turbine. Hence, the heat tiles most be inspected on a regular basis and damaged tiles must be replaced before they break. In Fig. 1, an impression of such an inspection is shown.

Fig. 1 Inspection of heat tiles in the combustion chamber from Siemens

The process of inspecting heat tiles requires a plant operator to shut down the turbine for multiple days and to let a member of the field service personnel enter the combustion chamber for inspection and maintenance. Since the combustion chamber is not designed for the comfort of a human, the process of entering it and moving around in it is not ergonomic. Furthermore, the person who performs the inspection needs to carry multiple tools (e.g. a notepad, a camera) with himself and uses these tools in an already uncomfortable ergonomic situation. Hence, it is in the interest of maintenance service providers to provide their service personnel with a tool solution that allows them to do their job hands-free, thus allowing them to move around more safely within the limited space in the combustion chamber.

The goal of the solution presented in this paper is to provide a hands-free tool that supports service personnel in identifying and documenting damaged heat tiles (and screws) and in creating a respective protocol (for a subsequent process in which damaged heat tiles are replaced). The order of inspection steps, the criteria for judging damages and the format of the protocol must be carried over from the existing process. The detailed steps in which the user interacts with the tools can be designed anew for maximum usability and safety.

The solution shall be realized by using smart glasses. Smart glasses allow a stand-alone support with hands-free interaction

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International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:10, No:10, 2016

[8]. Multiple published applications for the smart glasses in maintenance processes suggest the usage of augmented reality [10], [6]. In contrast to that, the customer preferred a non-see-through version. This wish is originated from the initial idea to transfer the existing paper documents on a wearable display equivalent. Existing development methods with a focus on a user- and context-orientation that can be used for conceiving a suitable solution are Usability Engineering of [7], the Usability Engineering Lifecycle of [5], and the guideline for User Centered Design (UCD) [3].

II. Method: User Centered Design

Designing a solution for the turbine maintenance requires a look into the possible interaction patterns between the turbine inspector and the supporting tool. Hence, the User Centered Design Method [3] is used. This method postulates four steps for designing a user-friendly and context-optimized solution. First, it is necessary to understand the use case (context), the user(s), and the technical and physical environment. Second, requirements for the solution's envisaged application should be formulated. Third, design solutions should be generated, and fourth, the solutions should be evaluated with respect to the usage requirements.

The following analyses describe the turbine maintenance, the inspector, his direct environment, and the portable device in detail. Subsequently, a paper prototyping approach is applied in order to generate possible design solutions. The results from the prototyping process will be tested by an expert and finally discussed with respect to the requirements.

III. Results

A. Task Analysis

The goal of the inspection process of the heat tiles in the turbine's combustion chamber is to control every tile whether it is damaged or not. As a support tool, a checklist is used that describes different types of damages and their manifestations. The field service member inspects all tiles in a predefined order and protocols the state of each tile. In a case where a tile is damaged, he has to distinguish which type of damage applies to which degree. Each damage level (i.e. the degree of damage) is associated with a corresponding activity that needs to be performed when that damage is identified (e.g. a high damage level entails a change of the tile). Altogether, the inspection of the combustion chamber comprises the inspection of 65 tiles. There exist eight different damage types and a range of one to seven activities for each damage type.

B. User and Environmental Analysis

The inspectors must have received a training before they are allowed to perform an inspection at the customer's site. The range of their age is wide, from young beginners to older experts. The inspectors are affected by the turbine's environment. They must climb into the combustion chamber through a small entrance. Since the temperature in the combustion chamber can be more than 60 °C and since they have to operate in a confined space inspectors have to wear protection suites, helmet, glasses, and gloves.

C. Technical Device Analysis

For this study, the use of a prototype of a smart glasses headset has been predetermined that has currently not yet been released to the market and that must therefore remain under non-disclosure. The headset is conceived for industrial use cases and features a rugged design. It consists of a headband comparable to that of an Oculus Rift and a single display that can be placed in front of the right eye. The headband is designed to be compatible with safety helmets and safety glasses. The display of the prototype features a SVGA resolution of 800x600 pixels, a size of an estimated 1.2 inches and it appears significantly larger than comparable devices such as Vuzix M100 or Google Glass [2]. The device features a preinstalled Android 4.4 operating system and it supports the Android voice command library, Bluetooth 3.0, and Miracast. User inputs can only be processed from voice commands or from touch inputs on another Android client that is connected to the headset through a proprietary connector app. Furthermore, the headset features a camera that allows for photographs and video recording in 800x600 resolution. The battery of the system shall supposedly last for four hours of active use of the system. While this has not been verified in the initial evaluation of the system, a few other limitations have been identified. The system's lack of Bluetooth 4.0 support limits its possibilities for connecting additional sensory devices to it which may become necessary for sensing the temperature within the combustion chamber and for sensing the user's health status. Also, the built-in CPU and GPU do not provide enough computing power for complex computer vision algorithms. Even though the final version of the prototype that shall be released this year might feature a more advanced piece of computer hardware, it can be assumed that the computer vision algorithms will still have to be outsourced to an external device in case they are needed.

D. Usage Requirements

The requirements are partially derived from the previously described analyses. Furthermore, multiple interviews with key users from field services and with work safety representatives have been performed in order to gather and elicit requirements. These requirements comprise:

1. Task-Related Requirements
   - Inspection time shall be decreased.
   - Accuracy and completeness of the identification of defects shall be increased.
   - It must be possible to create a documentation from the damages within the combustion chamber.
   - Completed tasks shall be protocolled automatically.
   - The status of every tile must be protocolled.
   - A list of tiles, that have to replaced, shall be generated automatically.
2. User-related requirements
   - Task complexity shall be decreased, especially for novices and older users.
   - The system shall be ergonomic.

– The new system shall not be designed for replacing experts by non-qualified users.
3. Technic-related requirements
– The system shall be able to display reference pictures of damage types.
– The system shall be able to take photographs.
– The system's power supply must last for at least five hours before batteries must be replaced or recharged.
4. Environment-related parameters
– The system shall be able to withstand strokes and scratches.
– It must be possible for the system to be combined with protection glasses.
– The system must remain fully functional in temperatures up to 50 °C.
– The system must allow for hands-free use.

Note that these requirements are not complete. During the requirements analysis, a total of 53 high level requirements were formulated.

E. Design Solutions with Paper Prototyping

1. Research Question

As mentioned before, the user has to deal with different influencing factors during his work such as a high ambient temperature and confined space. The current process of inspection requires the carrying of documents (e.g. protocols, check lists, etc.) and the filling in of the observed results. Due to the difficult environmental conditions, the procedure of filling in documents and keeping one's balance at the same time is not only physically demanding, it even involves the risk of injuries. A possible way to minimize that risk and to decrease physical strains is to provide the user with a system that allows the user not to use his hands for documentation but for safeguarding himself instead. Smart Glasses can satisfy this demand: the user has free hands during the whole inspection and communicate with the glasses by voice commands. The present question examined here is: what is the ideal GUI-design for a Smart Glass device that meets the requirements mentioned earlier?

2. Method

In order to generate design solutions, a paper prototyping [11] method is used. The goal of a paper prototyping session is one or more paper-based interfaces. These interfaces may include dynamic parts. It is possible to interact with the paper interface, by moving or changing piece of paper that represents the user interface elements. By this way, different ideas of a solution are generated. Furthermore, the paper-based dialog systems can be used for an upfront evaluation of the user interface together with an expert.

3. Material

For paper prototyping pieces of paper with different shapes and colors are needed. Furthermore, different pens, scissors, and glue should be available. The participants of the paper prototyping process are presented the original material that is used for the paper-based inspection: a checklist, a list with measures for different defects and a set of reference pictures of different defects. Finally, the participants receive a complete description of the use case and of the requirements for to system that shall be designed.

4. Procedure

The paper prototyping process begins with a presentation of the procedure, the use case, and the requirements. Subsequently, a short questions and answers sessions is carried before the actual prototyping begins. After the participants have completed their first prototype, an expert joins into the session. Then, the groups let the expert interact with the paper prototype who explains all his/her actions and his/her accompanying thoughts (thus implementing the thinking aloud method for qualitative usability measurement [4]).

5. Participants

Nine persons were involved in the prototyping Session. One person was the moderator, seven participants created the paper interfaces, and one expert tested the prototypes. The seven participants were between 21 and 34 years old (mean = 29.29, standard division SD = 4.61), with one female and six male participants. The education background of four participants was computer science, two participants had an engineering background, and one participant had a background in psychology. Four out of the seven participants had previous knowledge about smart glasses, three participants knew about turbines, and no participant had previous knowledge about maintenance.

6. Results of Paper prototyping

In the paper prototyping session, each group designed one interface prototype. These two paper prototypes are displayed in the following Fig. 2.

Fig. 2 User interfaces as results from the paper prototyping

Both prototypes feature multiple similarities and differences. They both display identification number of the currently inspected tile on the right top of the display. Furthermore, they both display a specific damage type, inviting the user to decide whether or not this damage type applies for the currently inspected tile. Yet, the damage type is located in different areas on the interface (top-middle vs. top right). Furthermore, both designs behave differently when the user specifies the inspection result for the damage type. In one prototype, the inspection result is displayed and the damage type that needs to be inspected next is displayed under it (as an additional line). In the other prototype the inspection result is hidden and the "next" damage type replaces the previous one.

Hence, one displays a history of inspection steps with their results while the other one does not.

Another similarity in both designs is the displaying of options for voice commands. In one prototype the commands are displayed in a column in the middle left, in the other prototype on the bottom of the display. In summary, three information types are displayed in both prototypes: tile identification number, damage type and options for voice commands.

Both paper prototypes feature the order of tasks that can be performed with respect to the interaction pattern (user-machine-dialog). The workflow for the inspection of one tile is shown in Fig. 3. This workflow describes the interaction between the inspector and the system. At any time, the user has only two decision options, yes or no. The workflow begins with the detection of one specific tile (with its unique identification number). Then, the system asks the user to check whether the first damage type on the checklist can be observed on the tile. If the answer is no, the next damage type is checked. If the answer is yes, then the system presents the user with the first possible manifestation of that damage type (from an internal list of possible manifestations). If the answer of the inspector is no, then the system subsequently presents the different possible manifestations until the user confirms one that applies. Subsequently, the next damage type will be checked. This dialog will be repeated for all tiles. One difference between the two prototypes was that one group presented the user with a confirmation prompt after each decision that he answers with yes.

For each manifestation, for each damage, type for each different type of tile (i.e. a triple configuration "tile-damage type-manifestation"), the system "knows" the corresponding activities that must be performed in order to solve this problem. Based on that information, a protocol with necessary activities that should be performed is generated automatically from the defects that the user has identified.

Additional considerations were made with respect to different designs for novices and experts. The group that had suggested an additional conformation prompt would omit that prompt in case of an expert mode. The other group suggested that experts should be allowed to break the predefined order in which tiles, damage types and manifestations for damage types should be inspected. Their idea was that the inspector should be allowed to give a voice command that consists of the combination of the identification numbers of a tile, a damage type and a manifestation of that damage type. The user would only use this voice command for the damaged tiles, and the system would assume that there exist no defects for all other tiles.

Both prototypes suggest that voice commands should be used for confirming or rejecting a damage type and corresponding manifestations. Furthermore, it should be possible for the user to request the displaying of reference pictures for a damage type or a manifestation that is currently displayed.

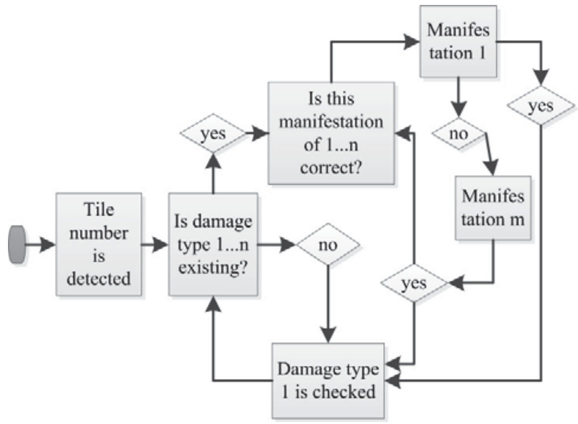

Fig. 3 Workflow of the inspection for one tile

Also both prototypes provide a function for taking pictures of identified defects. Yet, they both feature a different approach for that function's implementation. The first group suggests that the system should automatically take a picture of a tile in the moment when the tile is selected for inspection (which corresponds to the first step in the previously presented workflow). In the case where the inspector confirms at least one defect (i.e. the manifestation of one damage type), the system keeps the picture. In the case where no defect is identified, the system discards the picture. In contrast to that, the other group proposes that the taking of pictures should be actively triggered by the user. After the confirmation of a manifestation of a damage type, the inspector has the possibility to make a voice command for taking a picture.

After their completion, the two prototypes have been evaluated by an expert who knows the current procedure of inspecting the tiles in the combustion chamber. The expert was to use the prototypes without help and shared his decisions and thoughts by uttering them out loud. The evaluation showed that she/he was able to perform the inspection process using the prototypes without help. The expert praised both results for their easy understandability, yet the suggested a few improvements. First, she/he asked for an expert mode that would allow him to directly document the identified damage types (with their corresponding manifestations) using voice commands instead of having to "browse" through the preordered list of possible damage types and manifestations until the reaches the one that applies. She/he also mentioned that in expert mode she/he would wish for the possibility to decide which tile she/he wants to inspect next instead of having to follow a predefined order. Furthermore, she/he mentioned that she/he preferred the approach where a history of documented defects is displayed. Based on this expert feedback, the two different prototypes have been merged. As a result, a consolidated design of a graphical user interface, a corresponding workflow of interactions between the user and the interface and a set of voice commands is suggested. The graphical user interface always displays the identification number of the currently inspected tile, the name of the currently investigated damage type, (in case a damage type has been confirmed) the currently investigated manifestation, and the applicable voice commands. Additionally, the history of already identified defects (for the currently investigated tile) is displayed. The workflow is simple: the system presents the different tiles in the order of their actual arrangement in the combustion chamber. For each tile, the damage types (and their corresponding manifestation) are inspected in a predefined order. The voice commands are simple, too: they comprise only the answers yes, no, and reference. The taking of pictures and the generation of a protocol are performed automatically by the system. The suggested expert mode has been documented as a nice-to-have feature for an enhanced prototype that should be developed in the future.

7. Discussion

The objective of the presented study was to develop an assistance system for the maintenance of a gas turbine. As a design constraint, it was predetermined that the system should employ smart glasses and that it should be usable without hands. For simplicity, the scope has been narrowed down to the inspection of the tiles in a gas turbine's combustion chamber. As a result, the presented concept does currently only fulfill a subset of all requirements that have been gathered from the end users. While all requirements related to supporting specific inspection tasks have been fulfilled, multiple other requirements such as the envisaged decrease of inspection time and the accuracy and completeness of the identification of defects could not be evaluated in a meaningful way. Hence, a further usability test that compares the current paper-based process with the hands-free smart glasses approach presented here should be performed. Furthermore, multiple technical and environment-related requirements could not be considered during the paper prototyping process. For example, the resistance against heat, scratches, or shocks could not be addressed since the smart glasses hardware itself was not evaluated in this study.

IV. General Discussion

In the presented maintenance process for gas turbines a set of printed documents and paper protocols are currently used. Mostly due to the ergonomic disadvantages of this approach a smart glass based assistance system was to be conceived that renders the currently used documents obsolete and that allows for a hands-free inspection process. In order to develop a user-friendly and purpose-fit solution design, the User Centered Design method was applied. This paper presented an extract of the previous requirements analysis as a base for a paper prototyping session. The goal of that session was to design a graphical user interface and a corresponding workflow that describes the possible interaction of the user with that interface.

The first idea of the key users was to directly transfer the current work process to the new assistance system by letting the user view and edit the original documents on the smart glasses. The paper prototyping process led to a very different design. Instead of viewing and editing documents, a simple and repeating dialog between the inspector and the system has been designed. The knowledge about the order of the steps that need to be performed is "extracted" from the documents and is implemented in the system's internal workflow. This leads to a "step-by-step instructions" approach, like the suggestions from [9]. This knowledge about the steps can also be used to improve the system [1].

In summary, the main result of this study is a concept of smart glasses based hands-free assistance system with a step-by-step dialog to capture defects of tiles (in the combustion chamber of a gas turbine). Currently, the inspector has to fill out a checklist, has to decide which corresponding activities have to be done and has to write at least a protocol with the findings and activities. With the new concept, all these activities become obsolete, and the inspector can use his hands freely for better ergonomics.

The prototype of the smart glasses headset that is currently available in the project supports all the technical features that have been considered during the prototyping process. It is thus technically feasible and it is scheduled to be implemented by summer 2016.

Acknowledgment

This work has been funded by the BMBF – Germany within the research project ALUBAR. The authors would like to thank all their project partners and our external partners for providing us with early prototypes of their smart glasses headsets.

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