Assessing the Efficiency of Information Retrieval from the Digital Shadow at the Shop Floor using IT Assistive Systems

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Abstract: The increasing demand for customized products and thus the higher product variety affects the workplaces in the manufacturing industry. More complex work tasks raise the need of employees at the shop floor to access relevant information efficiently, which leads in turn to an increase in information density and complexity for them. Through the digitalization of production steps, this information is merely available digitally. Thus, the concept of the *digital shadow* is used to make this relevant information available at the right time. For this, assistive information systems have been widely researched. However, there is little research on a structured evaluation of assistive systems' efficiencies in information transfer to the employees at working stations. For the evaluation and comparison of the information transfer's efficiency, a modified version of the standardized Methods-Time Measurement method is used. In the study, different representatives of assistive systems, i.e. paper instructions, IT-glasses and hand-held devices are evaluated. Using a machine setter workplace at the Geberit Produktions AG, these assistive systems are compared. The results show that the applied Microsoft HoloLens and Huawei tablet, as representatives for IT-glasses and hand-held devices, lead to smaller error rates and significant time differences in the information processes compared to the paper-based work instruction. Moreover, questionnaires concerning the cognitive load and the assessment of the assistive systems regarding the ease of use, level of satisfaction and performance were applied in order to support the previous findings. The paper concludes by giving rules of thumb for the application of IT-assistive systems at the shop floor.

Keywords: Digital Shadow, Information Processes, Assistive Systems, Methods-Time Measurement (MTM), Shop Floor.

1. INTRODUCTION

Research in the field of assistive systems and mixed reality applications in the context of manufacturing has proposed a large number of visions, prototypes and systems, which were evaluated in production environments. Especially the use of IT-glasses and tablets is promoted widely. Since production methods change rapidly, automation processes become more important and the information density for the employee at the shop floor increases dramatically due to more complex production processes and a higher number of product variants. Thus, the worker faces a high density of information at each individual step in production and has to keep pace with the processing times of robots and machines to fulfil the task within a fixed cycle time.

In literature, a large number of assistive systems, like IT-glasses and hand-held devices, has been tested at manual assembly tasks and evaluated based on key performance indicators (KPIs) such as task completion times and number of errors, as well as additional cognitive questionnaires, expressing the subjective impressions of the workers [1,2,3,4,5]. Research also focused on the establishment of an alternative motion analysis in order to create an objective quantifiable evaluation method for manual assembly tasks [6,7]. However, the present motion analyses are either more product-specific or predominantly focused on movements without a specific consideration of the information processes. To this end, neither a method for evaluating information retrieval processes using IT devices exists nor is it evaluated in industrial work processes.

The presented paper uses an objective validation procedure for IT-supported assistive systems, based on the established Methods-Time Measurement (MTM) to determine relevant information processes of manufacturing tasks. For this, the tasks are divided into phases of mechanical work and information retrieval. These phases are further analysed regarding its basic motions. While for the phase of mechanical work, the classical MTM can be used, an extension of this method was proposed by Kubenke et al. [8] to also evaluate the information retrieval phase. However, this method was never validated in real industrial processes so far.

Based on a machine setting application, all relevant information needed by the employee at the shop floor is retrieved from the digital shadow of the machine to be set up. Hence, the paper describes the concept of the digital shadow and validates it as a concept for data management systems.

After a review on related work and a brief introduction of the extended MTM, the industrial use case at the Geberit Produktions AG will be described. The remainder of the paper shows the study setup and presents the achieved results. The paper then concludes with a discussion on these results and an outlook on future work.

2. RELATED WORK

2.1. IT-supported Assistive Systems

The IT-support of workers in production environments has been studied widely, i.e. the application of IT-assistive systems to support the worker in fulfilling the work task: Caudell et al. [9] were inspired by a drilling task at an aircraft manufacturing process. In their study, they used a Head-Mounted-Display (HMD) to support the worker by displaying the drilling positions. Zheng et al. [10] compared three different types of work instructions. They applied a paper instruction, IT-glasses, and a tablet and choose a car maintenance task to compare the work instructions. An overview of the recent field of studies is given by Büttner et al. [11] and Fite-Georgel [12] regarding mixed-reality technologies and different areas of application, i.e. logistics, maintenance, and others. Most studies included key performance indicators for the comparison of the assistive systems or work instructions, i.e. task completions times or error frequencies. Besides this, questionnaires were used for the subjective impressions of workers [3,11,12,13,14,15,16].

For analysing workplaces and assistive systems based on motion analyses and information processes, Card et al. [7,17] introduced a first model in the context of evaluating the performance times of keystrokes. The model is called “Keystroke Level Model” (KLM) and evaluates the time an expert needs to perform a certain task on the computer. Therefore, the model is limited to analyse computer tasks with a keyboard, i.e. when keystrokes are measurable. Another model based on a motion analysis is presented by Funk et al. [6] with the General Assembly Task Model (GATM). The GATM focusses on the time used for task-dependent and task-independent motions at manual assembly tasks.

In general, the information processes are not separated and researched clearly in the presented studies and models; they are seen as irrelevant or not quantifiable, or as already included in the process components.

2.2. The Digital Shadow of a Product

The so-called digital shadow of a product can help to overcome current constraints of data management systems, since it provides relevant information at the shop floor. The digital shadow is determined as the “sufficiently precise image of the processes within research and development, production and adjacent fields which are needed for a real-time capable evaluation basis” [18]. Regardless of a data management system’s naming as digital shadow, product twin [19], product avatar [20,21,22], or digital product memory [23], the product centric information management concept [24] is the core part: The mentioned concepts seek to implement information transparency and availability across the entire lifecycle [22]. They all incorporate a digital counterpart of a real product to connect the relevant information centrally [19]. The underlying idea is based on the fact, that for an individual product the physical product itself is the only direct link of all relevant information [21]. The potentials of this concept are usually allocated during the usage phase of a product, i.e. for service and maintenance [25,26]. Wuest et al. [27] research the specific example of a leisure boat having a product avatar in the form of a Facebook account, to communicate relevant information of the life cycle, for example for preventive maintenance. Besides, the concept is well known and strongly characterized in the aviation industry as the digital twin [28] following simulations based on real data.

However, as is can be seen from the definitions given above, the concept is also fully applicable for the *micro* product life cycle of production: “Product experts need information focused on the product” [29] and thus from the digital shadow, e.g. to optimize the flow of production by detecting bottle necks [30].Thus, the diverse application areas of the digital shadow are an important aspect of how to provide the contained information to a worker at the shop floor. Without an appropriate visualization, any information is of no value, as it cannot be accessed and used to add value.

Based on the findings of Kubenke and Kunz [8], the effectiveness of information transfer from the digital shadow to the employee at the shop floor is assessed in this paper. The results give an overview on how to display relevant information of the digital shadow to the employees at the shop floor. Therefore, this paper validates the digital shadow of a production machine as a data management system containing the relevant work instruction to produce the corresponding product, i.e. to set up a complex assembly station correctly. In doing so, we derive rules of thumb of appropriate visualizations.

3. CONCEPT

The proposed concept focusses on the identification of potentials of workplaces that can be supported by IT-systems. It is based on the separation of the complete work process into phases of “mechanical processes” and “information processes” and a further analysis with the help of the MTM method. However, the MTM method does not consider the information processes of phase two. The approach introduced in [8] states that even these information processes are finally measurable in their basic motions, which are performed by the worker to receive, procure or transfer the received information. Therefore, the information phases can be analysed with the help of the MTM method to receive time values, i.e. so-called Time Measurement Units (TMU), for further calculations. Based on these time values, the information phases are further compared depending on the applied assistive system, i.e. how time-consuming the information retrieval is with the paper-based or IT-supported work instruction. If the information phases encompass an essential part of the whole work process, i.e. the worker needs to retrieve the information between every working step, a significant potential for IT-support is given. Based on the information process times and related basic motions, the most suitable IT-system can be determined. For instance, if the worker needs both hands for the mechanical processes, an IT-glass is best suited. In general, the pursued concept serves as a decision base for the potential determination and support system selection.

With the MTM method, every performed basic motion of manual operations is analysed. Thus, this procedure can also be mapped on the manual operations during the information phases. The use of IT-systems might cause new manual operations, for example “click”, “touch”, “zoom”, and others, which can be analysed again based on the usual MTM basic motions, i.e. “reach”, “grasp”, “move”, “position”, “release”, and others. A correspondence map was shown in [8].

Regarding the determination of the most suitable IT-system for a potential work place, the work task has to be analysed beforehand. It is obvious that a bimanual work task should be supported by an IT-system, which allows free-hand operations. However, the user interactions operating the IT-device need to be evaluated as well, which can be done in a user study. The modified MTM concept has been already successfully realised in a user study at a manual workplace [8]. However, the task in this study was done in an apprenticeship workshop, but not in a productive environment. The paper presents the validation of the concept based on a second user study, performed in a productive environment using a machine setting work process with a high demand for information.

4. USER STUDY

4.1. Design

The presented user study was set up in a repeatedly measured experiment design. The test persons run two trials with the same conditions, but with different types of assistive systems. Besides a paper-based work instruction (which was used by all participants), a Microsoft HoloLens was used as representative for IT-glasses, or a Huawei tablet as representative for hand-held devices. For the statistical evaluation, the type of assistive system was set to be the independent variable. For the dependent variables, the information processes in MTM, the task completion times linked to the error frequencies, and the cognitive load evaluated with the NASA-TLX questionnaire [31,32], as well as the questionnaire for the assessment of the applied assistive systems were used. The assistive IT-systems were permuted over the group of test persons to prevent any learning effect.

4.2. Task Description

The setup of the user study was integrated in the daily working routine at the production plant of the Geberit Produktions AG in Jona, Switzerland. The study lasted over almost three weeks. The addressed occupational group of workers includes the machine setters at the production plant, who are working in a shift system, but independent of the production cycle. The task includes the preparation of the ultrasonic welding machine and the installation of tools for a specific program. Further, specific parameters have to be adjusted at the machine itself and the machine controller. In Fig. 1 (a), the idle ultrasonic welding machine is shown, which represents the initial situation for machine setting. In Fig. 1 (b), the machine setter has already installed the tools inside the machine and is almost done with the work task.

(a) (b)

Fig. 1. Ultrasonic welding machine (a) idle (empty), (b) with installed tools (Geberit Produktions AG, Jona, CH).

The conventionally used set-up instruction was paper-based and limited to the parameters, which have to be adjusted for the specific programs and tools. This resulted in an increasing error frequency due to a wrong chronological order of settings or lack of information where and when to perform the right action. For the user study, the instruction was prepared as a step-by-step work instruction, applicable for all different installation routines. In total eleven routines needed to be applied to the ultrasonic welding machine (see Fig. 2).

Fig. 2. Extract of the paper-based work instruction applied in the user study.

The paper-based work instruction was digitized for the IT-supported assistive systems. For the Huawei tablet, the document was saved in a pdf-format on the local network and was then stored on the device. For the Microsoft HoloLens, the document was saved as a PowerPoint presentation on the device and then displayed with a corresponding viewer app. Fig. 3 shows how a test person perceived the instruction while applying the Microsoft HoloLens. The same visualization of text and pictures is used for the tablet instruction.

Fig. 3. Digitized work instruction displayed with the Microsoft HoloLens.

4.3. Participants

24 workers of the Geberit Produktions AG, two female and twenty-two male, voluntarily participated in the user study. The subjects were aged between 20 to 60 years and employed as shift workers, shift supervisors, or process responsibles. Most of the participants had seen the ultrasonic welding machine before, but only a few of them set up the machine before. All had in common that the handling of the setting task was difficult due to its complexity.

4.4. Procedure

Each participant was introduced to the purpose of the user study and the different types of work instructions. For the Microsoft HoloLens, the test persons received a brief familiarisation time. The tablet was already known and regularly used in the production plant, as it is a standard tool to work with at the Geberit shop floor. After the briefing, the experiment started. After each trial, the participants filled in a NASA-TLX questionnaire, and finally the test persons were asked to complete the questionnaire for assessing the applied assistive systems and for demographic data. For the subsequent motion analysis, as well as for measuring the task completion times and error rates, the working processes were recorded using two cameras. The recording started when the test person received the assistive system. Over the complete group of participants, the order of the assistive system with work instructions was altered, i.e. the half of the group worked with the tablet and the other half with the Microsoft HoloLens. Every test persons passed a trial with the paper work instruction. Further, the applied work instructions differed in type and order, i.e. the first test person started the experiment with the paper work instruction, the second test person started with the tablet. In total, 48 trials were performed and recorded, 24 with the paper work instruction and twelve each for tablet and Microsoft HoloLens. A study took approximately one hour. The data was collected and then analysed by SPSS using diverse non-parametric procedures.

5. EVALUATION AND RESULTS

5.1. Motion Analysis

First, the recorded tasks were analysed with the MTM method. Afterwards, the information retrieval phase was separated and further analysed. The achieved results of the MTM were analysed using SPSS to identify significant differences in the information processes of the three applied work instructions and devices. The procedure included the testing of two groups, i.e. the paper work instruction compared to the IT-supported assistive systems, using the Mann-Whitney-U-test. To compare the paper work instruction, Huawei tablet and the Microsoft HoloLens, the Kruskal-Wallis-test was used.

The paper work instruction (M=14,754.50 TMU, SD=2,114.41 TMU) and the IT-supported assistive systems (M=12,240.97 TMU, SD=2,828.11 TMU), were evaluated using the SPSS, which showed that the application of the IT-devices resulted in significant lower information processing times (M=13,497.74 TMU, U=151.000, $p<0.05$), i.e. the test persons could retrieve, admit and transfer given information faster and more efficient during the work task while using the tablet or the Microsoft HoloLens. More specifically, the information processing times of the Microsoft HoloLens (M=15,329.97 TMU, SD=1,819.99 TMU) are significant faster, respective lower in TMU (M=12,240.97 TMU, U=144.000, $p<0.05$) compared to the Huawei tablet (M=14,692.25 TMU, SD=1,516.29 TMU). Comparing all three types of work instructions, the analysis exposed a significant difference (H=25.735, $p<0.05$) in favour of the Microsoft HoloLens. In Fig. 4, the diversification of the information processing times is shown.

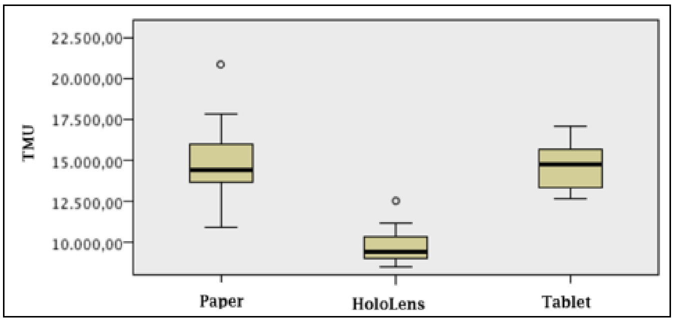

Fig. 4. Comparison of the information processing times of Paper, HoloLens, Tablet.

The boxplot of the paper instruction shows the largest variance inclusive one outliner. The boxplot of the tablet shows a smaller variance, but with the highest mean value of all. The values of the HoloLens have the lowest mean and variance values inclusive one outliner.

5.2. Task Completion Times and Error Rates

For the task completion times, the error rates have to be taken into account. During the task completion, a lot of test persons either tend to skip working steps or they lost track and needed some time to regain the overview. This situation appeared in particular within work instructions, which are hand-held. In detail, 16 test persons out of 24 using the paper work instruction had good task completion times, but also diverse errors, which were evoked by missing or repeated steps. The errors were serious and would have caused defective products. The same occurred when using the tablet. Ten out of twelve had fast task completion times, but also serious errors, which would have led to defective products or even deleting the program in the machine controller. For the Microsoft HoloLens, the task completion times were moderate and only one test person out of twelve performed an erroneous task, which was not serious. Hence, it can be concluded that the step-by-step instruction, only presenting the relevant information at one specific point in time, led to an effective performance and satisfactory results.

5.3. Cognitive Load Test using NASA-TLX at two points

Regarding the cognitive loads, assessed with the NASA-TLX questionnaire, the results showed no significant difference between all work instructions (H=0.596, p>0.05). In Fig. 5, the comparison of the cognitive load values of paper (M=33.72, SD=15.63), tablet (M=31.61, SD=16.62) and HoloLens (M=36.94, SD=16.66) are shown. The variance of all three work instructions is rather similar and shows no significant difference.

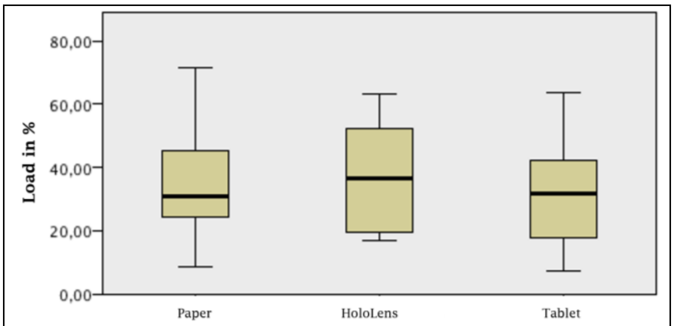

Fig. 5. Boxplot of the NASA-TLX values.

5.4. Subjective Assessment of the Work Instructions

The conclusive questionnaire, assessing the evaluation of the assistive systems, included the following three criteria: Ease of use, level of satisfaction, and performance. The assessment was based on the Likert scale, i.e. “1=does not apply” and “5=fully correct”. The values were evaluated again using non-parametric tests of SPSS. Regarding the first criterion “ease of use”, the results revealed no significant difference (M=4.2, U=268.500, p>0.05) between the paper-based (M=4.08, SD=1.02) and the IT-supported work instructions (M=4.313, SD=0.70). Considering the next criterion “satisfaction”, the analysis showed again no significant difference (M=4.24, U=215.000, p>0.05) between the paper-based (M=4.02, SD=0.96) and the IT-supported work instructions (M=4.46, SD=0.62). However, the analysis of the third criterion “performance” resulted in a significant difference (M=3.9, U=181.500, p<0.05) in favour of the IT-supported work instructions (M=4.21, SD=0.76) compared to the paper-based work instruction (M=3.58, SD=0.99). In total, the test persons evaluated the available work instructions as equivalent in the ease of use and level of satisfaction, but when it comes to the achieved effort and benefit, the Microsoft HoloLens convinces with its clear structured orders and intuitive operations. This underlines the result from the previous section, that the presentation of only the relevant information at a specific point is objectively as well as subjectively the most efficient solution.

6. DISCUSSION

The results of the user study validate the presented taxonomy regarding the setup as a decision base for information retrieval and IT-support at a real production environment. Considering the researched work process, the differences in the information processes could be pointed out and therefore, the potential for an IT-support could be confirmed. The IT-glasses performed best, and were most efficient in information processing times. This result is supported by the evaluation of the task completion times linked to the occurred errors. Using the Microsoft HoloLens, the test persons performed the most correct setting of the ultrasonic welding machine without making serious errors, which could lead to defective products. Every test person could decide individually where and when to open the app window to receive the needed information. Moreover, displaying only the actual step prevents the machine setters from losing track of the complex installation process. The overall results of the tablet and the paper work instructions revealed insufficient performances, mostly based on the serious types and high number of errors. These errors are evoked by showing more information at a time than actually needed.

Even though the subjective assessments regarding the cognitive load and the comparison of the work instructions did not show any significant difference in most criteria, the subjectively perceived performance was rated best using the IT-supported work instruction. This result supports the outcome of the motion analysis.

The general validity will vary depending on the investigated work places and available work instructions. Not every work station has the potential to be supported by an IT-assistive system. The more often the mechanical process of a task in the shop floor needs to be interrupted due to the need of information retrieval, the higher the potential for the application of IT-supported assistive systems is. The need to retrieve information is given, if the employee is unable to perform the task without the relevant information from the digital shadow. If the worker has memorized the working steps, an information provision is redundant and therefore assistive systems become obsolete in general. Following the user study at the Geberit Productions AG presented in this paper, the general applicability is given due to the fact that the applied MTM method is a standardized and widely accepted method for motions analysis, as well as by the fact that the defined terms and requirements have been strictly followed while analysing the recorded performances.

The performed user study highlights that different technologies for information visualisation need to be considered on the shop floor. In order to achieve the highest level of data transmission efficiency from the digital shadow to the employee, the following rules of thumb can be formulated based on the presented study:

- A need for the information retrieval has to be determined at the work place meaning that the times needed for the information processes are a significant portion of the overall working process or even interrupt the process.
- IT-assistive systems may be suitable for both, repetitive or non-repetitive work tasks. Regarding repetitive tasks, there has to be at least a constantly changing information demand that the information retrieval is necessary for the following tasks, i.e. the item number and the process of construction varies for specific products.
- The application of the MTM method serves as a universal evaluation method and can be adapted to almost every work situation. Especially in terms of human-machine-interactions or human-robot-interactions, the method provides a standardized and validated assessment basis.

To conclude, the results of this study are important and pioneering in the context of the digital shadow: This study shows that with the help of the Microsoft HoloLens the efficiency of a machine setting task could be increased by roughly 35%, based on objective MTM measures. The subjective results of the surveys underline these results. This implies, that the potentials of the digital shadow can be employed and lead to an effective data transmission process and thus to improved productivity on the shop floor. The employee receives only the relevant information, as they are attached to the machines' digital shadow. Having only the relevant information displayed, the productivity improvement is displayed in the TMUs needed for processing the information, cf. Figure 4: The processing of the relevant information is approximately 66% compared to the classical paper-based as well as tablet-displayed instructions.

7. FUTURE WORK

In future work, further applications of MTM, i.e. MTM UAS and other versions of the method, should be considered. The used MTM method is the basis and analyses extremely detailed every performed basic motion. In the case of the MTM UAS (universal analytical system), modules are formulated to enhance the motion analysis, i.e. reaching, grasping, bringing, positioning and releasing are combined as components and summarized in modules for a faster application. The same procedure should be performed with the emerging IT-supported operations. Optimizing the evaluation method will give the final basis to investigate suitable information provision technologies for the worker at the shop floor.

8. CONCLUSIONS

We validated an extended application of the MTM method in order to identify the potential of work places for IT-support as well as to set up a decision base for determining the most suitable IT-assistive systems for the specific work place. Furthermore, we exploit the potentials of the digital shadow by testing three different approaches of visualization information: Paper-based, with a tablet, and with data-glasses. The individually needed information was retrieved from the digital shadow of the corresponding production machine to be set up. The evaluation was validated at a work station in a real and ongoing production environment at the Geberit Produktions AG. The available working process included the preparation, installation and setting of an ultrasonic welding machine and represents a work place with a highly complex task and a high number of important steps to be accomplished. Due to the mentioned complexity, a correct machine set up is key for high productivity of the whole production process. Based on the structured approach presented, the results of the objective and subjective evaluation methods revealed a positive decision for IT-supported devices to display the work instruction, especially the Microsoft HoloLens, as the representative of data-glasses. This resulted in lower error rates, faster information processes and a more efficient work performance of the test persons. Based on our findings, we conclude with several rules of thumb to quickly define the areas of application of IT-assistive systems. Since the test persons are machine setters in real life but set up the mentioned welding machine irregularly and are hence not trained in this specific area of application. The evaluation of the information processes reveals highly relevant information not only for researchers but also for companies: We showed that the right information at the right time for the right person can improve production, when employing a combination of the concept of the digital shadow and the suitable IT-assistive system. In our example we showed that the efficiency of information lead to a decrease of the set up time of 35%.

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