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Cognitive-Oriented Process Information Presentation for Augmented Reality Assisted Product Assembly

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ABSTRACT

The information assistance during manual assembly process of mass customization production is indispensable in order to assure the assembly quality. The complexity of searching information and difficulty of understanding information brings about cognition burdens of workers under the varied and lengthy assembly process, where augmented reality (AR) can be an effective instruction tool. The cognitive issues of AR based information presentation for assembly guidance were discussed in this paper. The work about complexity of manual assembly process was analyzed both on error prediction and AR based cognitive perspective of visual assets. A four levels hierarchical task analysis was conducted for assembly process with three kinds of assembly stages, i.e. selection, installation and inspection. Cognitive reliability and error analysis method was taken to identify the possible human assembly errors during three stages considering the human cognitive activity and function. In order to provide right information at right place and right time for decreasing the assembly errors, the often used visual assets, i.e. 3D model, 2D annotation, text and video, were discussed for conveying assembly instruction intention in AR scenario. From the authoring complexity and potential cognitive efficiency aspects, different information presentation styles for three assembly stages were described.

Keywords: Human cognition, Assembly process, Augmented reality, Information presentation

INTRODUCTION

Assembly is an important stage of the entire product lifecycle, which is the process that two or more parts are joined together in order to realize the function. Assembly activities cover about 30–40% of product development time, up to 50% of manufacturing cost and average 40% of product cost (Krugh et al., 2016). It can be said that the assembly determines the product and quality of the product. Although automated assembly meets the requirements of mass production, there are still a large number of assembly activities of complex variant products that cannot be automated and require manual operation. The increasing operation complexity and the lengthy assembly process can cause human errors and influence the overall performance of the production, lead to decreasing of the assembly quality. In order to reduce the human errors caused by cognitive load during the assembly process of complex products, assembly information assistance system was indispensable and helpful (Hinrichsen et al., 2019).

Generally, assembly information assistance systems had shown the ability to reduce human errors and increase the productivity. Assembly manual was the most commonly used information assistant tool for delivering assembly instruction to operators (Kolbeinsson et al., 2023). The development of assembly manuals have gone through four stages and have four different types, i.e. paper manual, electrical file manual on computer screen, 3D PDF manual and AR manual (Wang et al., 2022). The complexity of searching information and difficulty of understanding information brought cognition burdens of workers, which decreased the work efficiency and result in the quality problem. In the traditional paper-based or electrical manual, text or drawings were usually shown for work instructions, where a high cognitive load was needed to understand the operation process (Werrlich et al., 2019). AR can superimposes the information in front of the users' view to facilitate their works. AR-based assembly assistant systems provide step by step visual instructions, which focus on how to identify tools, parts and materials, where to find them, and how to use them for assembly operation. AR allows various types of visual assets shown in front of operators for more clearly conveying the assembly process. Many studies have shown that the AR assembly manual can reduce human error rates and assembly times in performing assembly tasks compared to other instructions types (Wang, et al., 2016; Giridhar et al., 2020; Lavric et al., 2021).

Although there were various visual assets used for AR visualization (Li et al., 2019), there was limited research on the impact of different visual information on cognitive processes and error prevention. The cognitive issues of AR based information presentation were studied in this paper. By analyzing the assembly process complexity, the cognitive process was discussed for the assembly stages based on hierarchical task analysis. The Cognitive Reliability and Error Analysis Method (CREAM) was used to classify human assembly error and discuss who, when, where, what, how visual information was helpful to prevent these error in manual assembly.

PROCESS COMPLEXITY FACTORS AND ASSEMBLY TASK ANALYSIS

Assembly is a process involving many factors, such as human, machine, material, rule and environment. Studies had shown that AR had a positive effect on complex assembly processes in terms of assembly time, error rate, and other aspects (Bernardo et al., 2022). However, there was still no complete answer on how to measure the complexity of assembly process under the AR environment. The impact factors of assembly complexity were numerous, and the evaluation objectives vary. The existing complexity research mainly focused on the convenience of operations. Kiyokawa et al. (2023) gave a comprehensive summary of assembly difficultly and complexity from three aspects, i.e. system, product/object, task. The related design, operation and sequence complexity was classified and many factors were physical related characteristics (Richardson et al., 2006; Samy et al., 2010), e.g. the number of parts, shape/symmetry, number and position of fasteners. The aim of these work on complexity was generally used to predict product assembly defect caused by human or human-robot task allocation.

Many research had focused on the human performance assisted by different kinds of visual assets (Michele et al., 2022). Few studies had analyzed complexity from the AR cognitive perspective of visual assets. Radkowski et al. (2015) presented that the complexity of visual features and assembly tasks might influence the effectiveness of AR assistance. They divided the degree of difficulty into low and high level and different visual assets, e.g. text on screen, static 3D models, one or multiple 3D arrows, animated 3D models, 2D sketch, were used to form a metric. But they did not explain what was the degree of task difficulty under AR scenario. In the experiments of Deshpande et al. (2018), average time to install, different arrangement of parts, multi transformation of parts and multiple patterns in the structure were more important to assess the factor of installation complexity when AR information was used. During part selection phase, the definition of low and high complexity task was that whether there was more interference parts with a similar shape (Yang et al., 2019). Petrone et al. (2019) used a 3D puzzle ball to classify the complexity by color-coding the pieces that were identical so that the users could easily distinguish the pieces. Three degrees of complexity, i.e. easy, medium and difficult level, were evaluated from entropy dimension, which was calculated based on the total number of parts and different parts quantity in product (Bendzioch et al., 2019).

Apparently, the complexity of assembly process was tightly related with the assembly task (Fast-Berglund et al., 2013; Mattsson et al., 2020). In order to determine the general tasks required in the assembly process, hierarchical task analysis (HTA) was used for task description. Assembly tasks can be described as discrete operations among parts and devices (physical elements such as tools). A task is typically represented as a series of consecutive steps. In general, each step has three iteration activities, i.e. selection, installation and inspection, with total seven main operations (see Figure 1). The identified operations in HTA will be mapped to the cognitive behavior for AR assistant assembly instruction. The three stages/activities were explained as follows.

- Selection activity: The operator firstly identifies the part/tool (PT) to be assembled/used at material preparation area, and then he will move his hands and pick/grasp the PT in order to proceed the next installation activity.
- Installation activity: The operator finds the location of PT in the assembly, moves part to its place. During this phase, the PT will be orientated, adjusted, aligned and inserted to its final location. After the PT is placed at it's correct location, the connection operation will take place. The fastening, seal, gluing or rivet operation will be done to join the parts together.
- Inspection activity: The state of a connection will be checked, such as missing parts and incorrect position. Some measurements will also be applied for required assembly quality, such as the distance or depth of parallelism. At last, the assembly data will be recorded to information system.

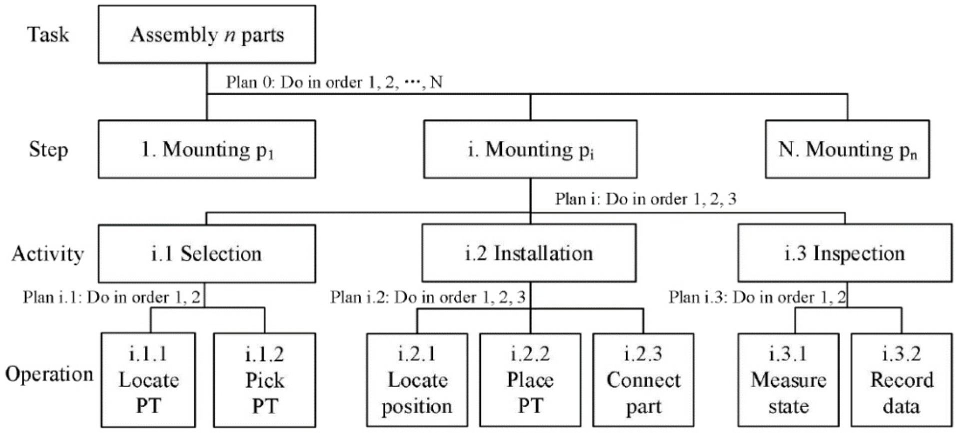

Figure 1: Hierarchical task analysis of human assembly process.

COGNITIVE RELIABILITY AND ERROR ANALYSIS FOR MANUAL ASSEMBLY

Many human assembly errors had been identified in literature (Yaniel et al., 2021). But deeply analysis was lacked from correlation among assembly task, assembly errors, cognitive activity, cognitive function and required information aspect. The Human Reliability Analysis (HRA) method had been developed to quantify the probability of human error when performing specified tasks (Pasquale et al., 2018). Based on task analysis, the HRA techniques, e.g. CREAM, HEART (Human Error Assessment and Reduction Technique), SHERPA (Simulator for Human Error Probability Analysis), and THERP (Technique for Human Error Rate Prediction), provided support to assess the possibility of occurrence of human errors. HRA methods were initially proposed and mainly applied in safety critical industries. They were rarely used in industry assembly systems. Therefore a human cognitive behavior model should be formalized in order to describe human cognitive processes and errors during assembly process. In this paper, CREAM was used to analyze the assembly cognition activities and the potential manual errors based on the HTA in Figure 1.

According to CREAM, cognitive process is the controlled use of existing abilities (skills, procedures, and knowledge) and resources. Each typical cognitive activity can be described by a combination of the four cognitive functions it requires. The four cognitive function is Observation (O), Interpretation (I), Planning (P), Execution (E). Each function is associated with different cognitive activities. There are total 15 cognitive activities, i.e. Co-ordinate (CO), Communicate (CM), Compare (CP), Diagnose (DG), Evaluate (EV), Execute (EC), Identify (ID), Maintain (MT), Monitor (MN), Observe (OB), Plan (PL), Record (RD), Regulate (RG), Scan (SC), Verify (VF). The cognitive demands of human assembly activity and the potential errors is shown in Table 1.

For assembly selection activity, locating and then picking the current step part/tool is the main operation. The related cognitive activities are OB, SC, ID, PL and EC. The O, I and P, E are the cognitive function for locating and picking respectively. The missed and incorrect selection are the potential human errors during this stage. For installation stage, placement (locating and placing the part/tool on the right the installation position) and connection are executed, and different cognitive activities and functions are required, where the results errors are the incorrect assembly position/orientation/sequence/-force et al. At the last inspection stage, measurement and recording are carried out, where missed/incorrect insertions/reading always be the human assembly errors.

Table 1. Cognitive orientated assembly error analysis in different assembly acclivities.

Assembly activity	Assembly operation	Cognitive activity	Cognitive function	Process/result errors
Selection	Locate part/tool	OB, SC, ID	O, I	• Missed part/tool • Wrong locating
	Pick part/tool	PL, EC	P, E	• Incorrect part/tool • Incorrect sequence • Incorrect quantity
Installation	Locate position	OB, SC, ID	O, I	• Wrong locating
	Place part/tool	CO, PL, EC, RG	O, P, E	• Incorrect position • Incorrect orientation
	Connect part	CO, PL, EC, RG	O, P, E	• Missed connection • Incorrect join sequence • Incorrect join force • Inadequate connection • Mismatched connection
Inspection	Measure state	EV, EC, VF	O, I, P, E	• Missed inspection • Non standard check • Incorrect reading
	Record data	EC, RE	I, E	• Missed recording • Incorrect recording

COGNITIVE-ORIENTED INFORMATION PRESENTATION FOR ASSEMBLY INSTRUCTION UNDER AR ENVIRONMENT

In order to instruct or reminder the human operators, different visual assets, e.g. text, video, animation, 3D model, picture and sign, can be superposed in the view. From the cognitive aspect, each visual asset has differentiated characteristics and need different level mental resource to learn/understand. How to present these visual assets for every assembly operation is related to assembly quality and efficiency. Although there were some design rules or guidelines in the literature (Chimienti et al., 2010; Rolim et al.,2015), no agreement was reached for the best way of assembly visual asset presentation based on AR (Agati et al., 2020).

The most important factor of information presentation in AR is the cognitive requirement for the assembly operation in HTA. In the review paper of Michele et al. (2022), the auxiliary model, product model and text was common used for task locating, assembly operating and checking respectively. In order to describe the assembly operation, what-how-why classification was proposed according to what was displayed, how it conveyed information and why it was used. Lavric et al. (2022) used what-where-how to present AR assembly assets, and the assembly operation was described briefly in "what", the operation physical location was indicated in "where" and the way to perform was described in "how".

In this paper as shown in Figure 2, we proposed a 4W1H (who, when, what, where, how) method of AR information presentation for cognitive assisted assembly. We used who to indicate the operator of the current action, when for assembly activities. What meant the visual asset type, where implied the position of the visual asset in augmented view, and how was the state of the displayed visual asset. In-situ positioning mean the visual asset overlaid the exact location of the assembly part in 3D world coordinate system (I3DR) or 2D screen coordinate system (I2DR). A predefined position in 3D world coordinate system (P3DR) or 2D screen coordinate system (P2DR) were also used for placement of visual assets. If the content, appearance, color, or position of visual assets remained unchanged in the view, the state of assets was static. For the visual asset type, we only discussed the four styles as follows.

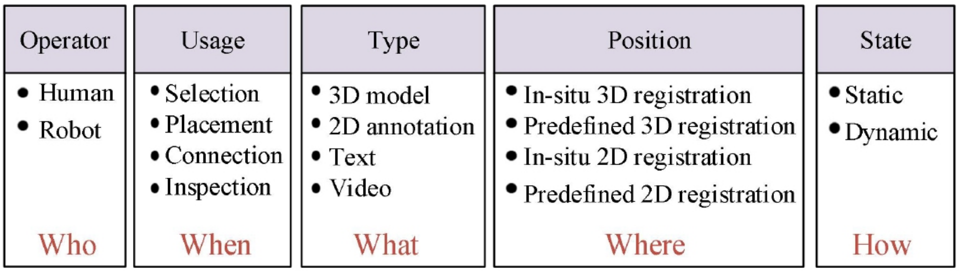

Figure 2: Who, When, What, Where and How for AR assembly information presentation.

- 3D model (3DM): The models have two classes, product or auxiliary model. It can be 3D virtual models of product/parts/connectors/tools/machines and obtained from CAD design stage. In AR scenario, they are the digital and visual representation of real objects, which can be visualized in solid or wireframe mode. The model can also be auxiliary models, which are used for abstract presentation to delivering hints or implicit instruction to the operator. The 3D arrows, circles and positioning boxes are common auxiliary models used in AR. The 3D model can be displayed statically or dynamically in AR.
- 2D annotation (2DA): In order to mark the objects in the AR, annotations (e.g. 2D positioning box, text bounding box) are used for attention attraction. They are usually registered in 2D screen coordinate system.

- Text: Text is the common way to convey process information and is easy authored in AR. But the long text is hard to read in AR because of the limited view. Short text is the suitable choice for assembly instruction in AR.
- Video: Some complex operations can not be clearly described using static or animated model. It is also hard to understand if text description is used. During AR assembly training, such complex operation can be demonstrated by videos, which are transcribed based on the real operation of experience workers.

In order to enhance cognition, improve efficiency, and avoid errors, we designed divers information presentation for AR assisted assembly considering the characteristic of different assembly activities/operations (see Table 2). First, the sequence and quantity errors in Table 1 were desired to be eliminated based the step-by-step action decomposition for each parts/connectors. Second, the missed operation in selection, installation and inspection stage would be avoided attribute to the exactly positioning of the augmented visual assets for clearly understanding. Third, by integrating assembly state checking function with feedbacking function for AR visualization, the incorrect position/orientation and missed components would be displayed to warn the operators (Zhao et al., 2023). Lastly, more digital measurement tools were used in shop floor, the measurement reading was recorded automatically and human reading error would be eliminated. Of course, different visualization styles had various amount of virtual assets, which had varied authoring complexity. Under some complex situation, one style was not enough for clearly describing the assembly operation and two or three presentation styles (e.g. 3DM+text) were simultaneous used for showing the assembly intention. From the aspect of cognitive efficiency, 3DM and video style were more easy understood comparing with text and annotation. Figure 3 shows several AR assembly information presentation examples of our past works. The different visual assets (what), registration methods (where) and states (how) are shown for assembly activities (when). The placement and connection are installation activities in Table 2.

Placement (3DM, P3DR, dynamic) All parts installed earlier and current step part	Placement and connection (3DM, I3DR, static) Two parts and arrow	Placement and connection (3DM, I3DR, dynamic) + (text, P2DR, static) Part/tool/two screws	Inspection (2DA, I2DR, static) Boxes, text for installed or missing part

Figure 3: Who, When, What, Where and How for AR assembly information presentation.

Table 2. Category for AR assisted assembly information presentation.

Tasks (when)	Content style (what, where, how)	Authoring complexity	Cognitive efficiency
Selection	3DM of positioning box, I3DR, static or dynamic	Medium	High
	3DM of objects, I3DR, static or dynamic	Low	High
	3DM of arrows, I3DR, static or dynamic	Medium	Medium
	2DA of bounding box, I2DR, static	Low	Medium
Placement	3DM of objects, I3DR, static or dynamic	Low (static) High (dynamic)	High
	3DM of arrows, I3DR, static or dynamic	Medium	Medium
Connection	3DM of objects, I3DR/P3DR, dynamic	High (I3DR) Medium(P3DR)	High
	Numeric text, P2DR, static or dynamic	Low	Low
	Video, P2DR, dynamic	Low	High
Inspection	Video, P2DR, dynamic	Low	High
	3DM of objects for assembly errors, I3DR, static or dynamic	Low	High
	2DA of box or text for assembly errors, I2DR, static	Low	Medium

CONCLUSION

Augmented reality based information presentation for assembly instruction demonstrated more and more benefits during manual operation. The relation among the assembly complexity, information presentation and cognition was still unclear. In this study, hierarchical task analysis was used to construct a four levels assembly process with three kinds of assembly activities. The human errors of these activities were analyzed based on CREAM. Several assembly information presentation styles in AR were described using 4W1H method. The assembly cognitive experiments will be conducted in the future to validate and improve the information design. The study can provide information support for personalized and differentiated requirement of operators in Industry 5.0.

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