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Authoring Tool for Automatic Generation of Augmented Reality Instruction Sequence for Manual Operations

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Abstract

Despite the large-scale digitalization and automation of production lines, human operators still play a vital role in the shopfloor. Operators provide flexibility and agile responsiveness with their actions, as well as capability to react autonomously based on their technical knowledge and experience. Bridging the gap between modern digital systems of information creation and management and humans in the shopfloor is a current challenge for both the academia and the technology integrators. One emerging way for delivering instructions to the operators is Augmented Reality (AR). AR allows the visualization of the instructions in the operator's field of view, using digital designs, animations and text instructions. As this technology gains increasingly more ground in the shopfloor, there is a need for agile generation of content, automatizing most of the instructions' generation process. Towards that end, this paper presents an authoring tool for generating digital instructions for manual operations. The authoring tool allows the identification of the (dis-)assembly sequence of a product and also to include intermediate manual operations, such as surface treatment, and visualizations. In order to determine which assembly tasks and instructions are the most commonly needed, contextual inquiries were conducted in collaboration with the industry. These findings, together with the existing literature on manual processes on the shopfloor, served as a starting point for a taxonomy of assembly task types that are also presented in this paper. The taxonomy serves as a guide to define the processes on which digital instructions and visualizations can be provided. The result can be delivered as digital on-screen instructions or as an augmented reality application that may target mobile devices and headsets. The proposed approach is validated in an industrial use case of a compressor assembly.

Keywords: Assembly; Augmented reality; Computer aided design (CAD)

1. Introduction

As digitalization affects most practices in modern manufacturing, so does for technical instructions transfer. There is an effort to shift from traditional on paper manuals that lack the interaction and the feedback mechanisms to digitalized approaches. Nowadays, the operator is not receiving instructions that require a strong technical background to understand, as it did for the traditional methods. On the contrary, modern applications with 3D instruction visualizations that support interaction are easier to perceive.

Augmented reality (AR) is an example of an emerging technology that contributes towards the improved delivery of information to the operator, on-time for completing the assigned tasks. This novel approach in instruction visualization has found fertile ground in manufacturing, in divergent applications [1], but most applications are tailored made for a specific case and lack the tools for automated instruction development.

Towards this end, this paper presents a tool for authoring instructions for manual operations that can then be visualized using augmented reality. This technology enables 3D projection

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of the instructions in the operator's field of view, enriched with animations and text descriptions. The proposed approach considers how to maximize data retrieval from CAD files, including an automated way of generating assembly instructions, as well as the functions that allow instruction generation for more complex operations. The proposed approach is then tested in a use case of a compressor assembly.

The rest of the paper is structured as follows: section 2 describes the current state of art; section 3 the operations taxonomy; the developed authoring tool and its functions are included in section 4; section 5 shows the resulting AR application and section 6 its validation in a industrial use case; section 8 summarizes the results and future work.

2. State of the art

The last decades, manufacturing has shifted towards offering multiple personalization options in the products, considering multiple product variants and options. Thus, increased flexibility combined with higher production rates is essential. Human operators play a critical role in offering the desired flexibility, being able to follow dynamic instructions and collaborate with robots and machinery in the production [2]. Human operators are capable of performing a large spectrum of operations, adapting to the requirements of each case and providing solutions and agile feedback to unforeseen issues. Thus, novel approaches focus on how instructions reach the operator by maximizing the utilization of existing data, while also establishing a two-way feedback stream [3]. Currently, there are a lot of applications that target how digital instructions for assembly operations may reach the operator; despite that, there is limited work available on how digital instructions may be generated for other manual operations.

There is a range of commercial platforms providing support for creating and managing digital work instructions. Those systems differ in their inputs and their authoring options. Systems like Azumuta [4], Manual.to [5], Proceedix [6] and Zaptic [7] allow to include imported illustrations into their work instructions. While other platforms (e.g. Dassault Systèmes, SAP, VISCOPIC) offers the functionality to use CAD data and create illustrations directly to a 3D viewer. Standardly, the (imported) multi-media illustrations are just unedited provided to the operator on the work floor. eFlex systems and VKS provides the tools to manually annotate the imported images with arrows, signs, texts, etc. On top of that, platforms that enable the generation of AR instructions have started to reach the market, such as Vuforia Work Instructions [8], but the guidance is based more on photos, videos and 3D arrows, with limited utilization of CAD data. Additionally, these platforms are focused on simple instruction giving, and lack the templates to provide instructions for manual operations combined with the corresponding technical details.

Work instructions authoring platforms require from the process engineers that they are acquainted with the operation sequence. The engineer needs to manually create the visual content of each step, including text, 3D geometry and selecting a convenient aspect to visualize it, which can be a time-consuming task. Tools for automatic sequence extractions are not yet widespread, though there are some examples available in literature [9]. Authoring instructions that are directly available in AR or VR applications usually requires a setup around the operator's workstation, thus reducing their reusability in multiple stations and/or dynamic tasks [10].

The transition towards systems that include AR-based instructions is a novel target of manufacturing. An ever-increasing number of studies and industrial validation scenarios prove its value in information delivery in production, including safety warnings and production status notifications [11]. Its applications in manufacturing have started from offline training operators supporting learning by doing on an actual setup [12] and to improve product design visualization and conceptualization, comparing part designs with existing components [13]. Nonetheless, contemporary applications consider it even for applications in the shop floor. AR is providing a sophisticated interface for real-time communication between the operator and collaborative robots in the shop floor [14]. Despite the promising results, adoptions obstacles, such as lack of organization-wide business models and system adaptation roadmaps that follow a standardized process, limit its adoption in the common practice [15].

Summing all up, it is evident that both literature but also technology integrators work towards developing platforms that deliver digital work instructions in manual operations. Additionally, augmented reality is proving to be an effective way to share digital information on the job that can use data from various digital systems from a modern production system. Towards that end, this paper presents a system that uses an authoring tool for creating digital work instructions on manual operations and an AR application that may use this information to guide the operator during the task. The application also considers customization of the instructions to match with the operators' needs.

3. Taxonomy

A taxonomy was developed to create a categorization of common assembly tasks and to support the design of the proposed software. The development of the taxonomy was supported by the findings obtained from contextual inquiries at manufacturing companies in Belgium and informed by the state-of-the-art literature on manual operations taxonomy.

A literature review provided insights on what types of assembly tasks and categorizations are usually reported. Rampersad [16] defined a set of six different operations (Feeding, Handling, Composing, Checking, Adjusting, Special processes). Lohse [17] built further on the task types proposed by Rampersad. The framework of Lohse put forward three different main types of functions possible in an assembly process; a) Task, Operation, Action. Each of the proposed functions were subdivided into a broader set of more specific functions. Besides grouping the process into different functions, he also proposed a taxonomy to define the hierarchy of assembly equipment. Swift and Booker [18] described a set of operations or tasks that can be part of the assembly process; a) Feeding, b) Handling, c) Fitting, d) Checking, e) Transfer. The execution of these operations depends on whether the steps are processed manually by a human operator or are assisted.

Besides diving into the literature, visits to manufacturing companies were organized in order to derive assembly task types from real-live use-cases. These contextual inquiries [19] were performed at two Belgian manufacturing companies (see Fig. 1 below). The objective of these company visits was to gather contextual information on the assembly processes they perform daily. In each company, an assembly worker during the assembly process by making screen recordings and gathering information about critical tasks in the process during about 1.5 to 2 hours was observed.

Fig. 1: Operator performing assembly operations during one of the inquiries

The generalized set of tasks was also discussed at several meetings with stakeholders (a.o. manufacturing companies and technology providers in the industry). By creating this taxonomy, templates of common industrial tasks were introduced, and define AR settings and instructions accordingly. After the classification, these templates were translated to useful AR visualizations to support the assembly process and inform the operator, and more specifically critical tasks and operations that are present in this procedure. Based on the state-of-the-art and outcomes of the contextual inquiries, a set of assembly task types was defined, which will be further discussed in the following subsections, based on which the authoring tool is developed.

3.1. Preparation

This type of operation covers assembly steps that take care of preparing material or part for a subsequent assembly step. We saw in both use cases (in the contextual inquiries) tasks that fit this category. Examples are preparing screws or bolts (removing plastic), preparing a glue gun with the correct filling, etc. A key element in these tasks is that they do not make changes to the main assembly setup. Additionally, these steps are not always performed by the operator of each work cell but they are prepared in bunches and the parts/tools are then provided ready to be used.

3.2. Pick and place

A large number of operations that were observed during the contextual inquiries belong to this category. These tasks include picking up material at a certain location, and assembling it at the main assembly setup, usually assisted by a tool. Examples are tightening screws, applying bolts, etc. As manual operations mainly consist of this kind of operations, a special attention should be given to methods that support and enhance the operator's experience in these operations.

3.3. Surface treatment

Surface treatment tasks were present in both observations, within one mentioned as a very critical task. Surface treatment category covers a large extend of operations that may be connected with surface finishing or giving certain properties to the material. Surface treatment can be either very delicate, e.g. applying glue following a certain path at a certain pace. It can also be a task in which the area itself is not precisely defined, e.g. air blowing or sanding an area.

3.4. Quality inspection

It is assumed that quality inspection is present in mainly all assembly processes. This includes checking for damaged parts before using them in the process, ensuring correct gear is used, correct assembling in respect to tolerances, etc. In the observation during the company visit, it appeared as e.g. the distance between a set of holes was important so as to ensure alignment of parts. Quality inspection and matching with specific requirements is one of the most important manual operations that humans perform in the production line and finding ways to automate its visualization.

3.5. Handling

Handling deals with tasks that involve the movement or transportation of certain material. In the observations, some of the assembly tasks required that certain main components are moved/transported towards the main assembly setup, assisted by e.g. a pulley. Moreover, this category includes special handling instructions that the operators is given, due to potential hazards in mishandling a part. Such an example is handling parts with sharp edges. In this case where the operator's safety is directly involved, special care should be given to securing that the operator will receive the safety warning notification.

3.6. Adjusting

From the observations and discussions with the involved industrial partners, it was discovered that adjustment is also a specific type of manual task to consider. It includes the alignment and calibration of the components in the assembly.

3.7. Other

As there can be any other types of tasks, we provided this category for the system's extensibility.

4. Authoring tool

In order to materialize the aforementioned taxonomy into a tool that will enable the user to generate work instructions, an authoring tool has been developed. Following the taxonomy and the general trend that manual tasks mainly revolve around pick and place operations, the tool focuses on supporting the generation of assembly operations by automating a large portion of the process. The workflow of the proposed approach is visualized in Fig. 2 below.

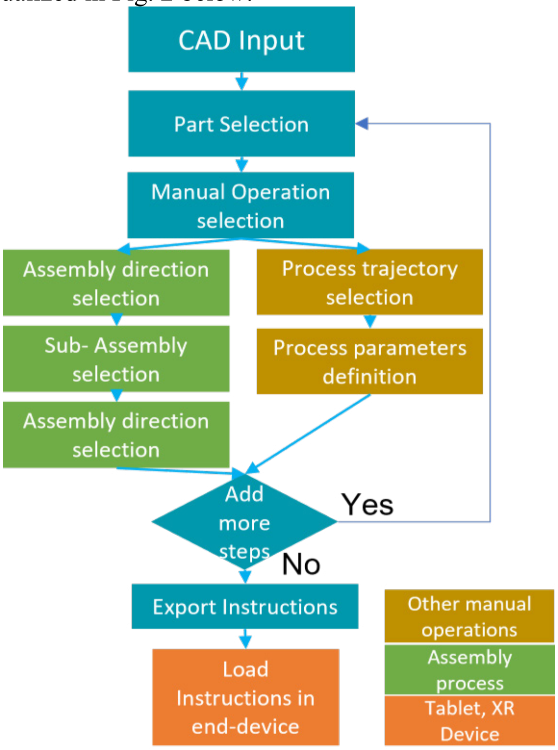


Fig. 2. Workflow of the proposed approach

To facilitate the process, an algorithm has been implemented to automatically extract an assembly sequence from a CAD model. As detailed explained in the paper [20], the tool will in fact determine the disassembly sequence, by evaluating in which order parts can be removed out of the assembly without colliding into other parts. Heuristic rules are used to assess if the visibility of parts is blocked by other assembly parts, this under the assumption that no visual obstruction means also no physical obstruction for removal. Once a direction is found wherefrom no other components hinders the visibility upon a part, the removal of this part is added to the disassembly sequence. The algorithm may automatically define the sequence for the majority of the parts, calculating also the axis and direction of dis-assembly. The assembly sequence is then derived by inverting the disassembly actions. The introduction of this algorithm reduces the time required for generating the instructions. The process engineer can then modify the order of the assembly steps, based on their own insights, and add intermediate steps for manual other operations in the sequence, like gluing and surface treatment.

Each of the processes, defined in section 3, require specific details to be set for their accurate definition and avoid misunderstandings in the production line. For example, in surface treatment processes, the user needs to define the surface or the trajectory that needs to be followed, as well as some technical characteristics, such as a path, width and velocity. These values are also used to make the instruction's visualization more immersive, as the tool motion in the instruction's visualization matches the velocity that the process should be performed (Fig. 3 and Fig. 4c). In each operation, the authoring tool interface includes fields for the operation engineer to provide the required technical details for each task. To facilitate the user, default values are provided for each field, based on common practice values provided by the companies and/ or the literature.

Another example of a common manual operation that is included is drilling. Flexible material removal processes are still a strong part of how human operators may affect the production. Thus, in the authoring tool the user may point on a part where the holes should be and provide the corresponding details (diameter, depth). Moreover, the authoring tool includes processes that reflect to product quality assessment and allow the operator to evaluate that the provided parts and the process itself are performed correctly. An example of such process that is implemented in the developed authoring tool and how it transforms in AR is tolerance measurement (Fig. 3d).

Additionally, the authoring tool allows the user to provide work cell specific information that may support the operator in the process. Especially in the case where the workcell is equipped with trays or boxes, the operation engineer may include in the task information the box in which the part is. The authoring tool includes some default templates of boxes formations commonly used in production, on top of which the user may define the position and each step define the box's ID where the part is. This information is then used in the AR application to guide the operator (Fig. 4a).

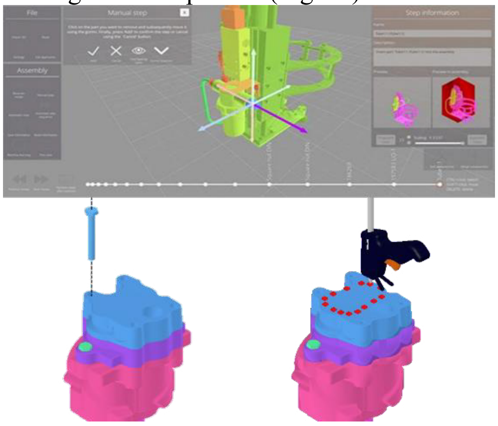


Fig. 3. Preview of instructions in the Authoring tool

In the meantime, illustrations (images and videos) are automatically created, using CAD geometries and the assembly direction details. The engineer can edit the proposed digital instruction, by changing arrow colors and image perspective, to make them clearer. The tool collects all operational information, like the insertion direction of a part (automatically derived) or the gluing trajectory (manually indicated) and export them in a standardized format (JSON) which can be used by other integrated tools. The AR application can then use this information per step (geometry, animation direction, or trajectory, tools) so as to generate the AR instructions.

5. Augmented Reality application

After the operation engineer defines all the steps of the sequence, the output can then be used to automatically generate AR instructions. The developed AR application exploits the data specified in the authoring tool to create an immersive feeling for the operator. In each step of the process, the AR instructions include a) an animation that shows where and how the part should be assembled, b) text instructions, c) a scaled down static visualization of the already assembled parts, where the new part is shown in correspondence with the previously assembled parts and if available d) instructions that show in which box the part is. Additionally, whenever a tool is required, such as screws, the AR application automatically visualizes the tool, together with the part to be assembled.

In the case of visualization of an operation that requires to follow a trajectory under specific conditions, the instructions are shaped around these conditions. Examples of such processes are gluing or welding, where the user needs to follow a path using a tool, keeping a specific pace and securing that the width of the result is following the set restrictions. In Fig. 4 below, the key features of the AR application and how different manual operations are depicted are presented. Providing this level of detail to the operator, it reduces the possibility of misunderstanding (either due to lack of expertise or misinterpretation) and reduces the errors made in the shopfloor.

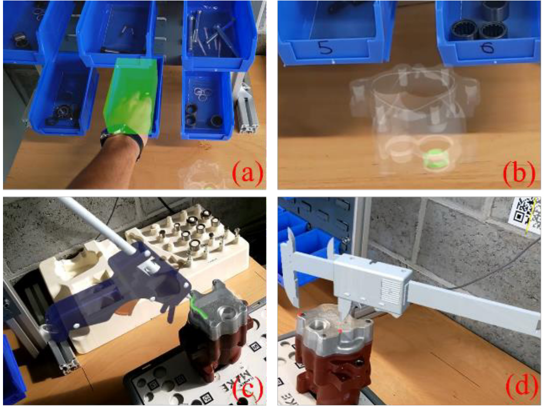
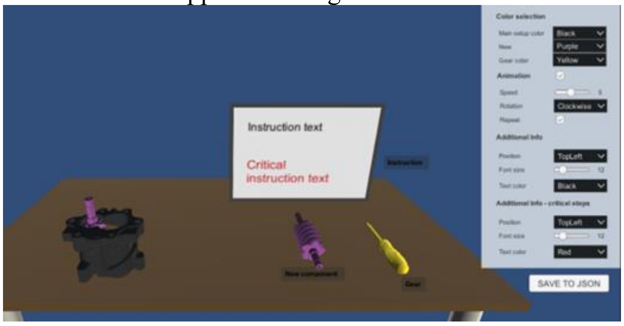


Fig. 4. Key supportive features of the AR work instructions application: a) correct box highlight, b) Transparent supportive visualization to show parts inside previous steps, c) gluing, d) tolerance measurement

The AR application also provides a set of features to support instruction customization in order to better support the operator needs. Customization allows for better adaption of the AR instructions to the work environment of the operator. The customization can be applied to different aspects of the instructions (Fig. 5): object or path color, animation (pace, rotation, frequency), and textual layout (position, color, font size). The customization features are based on the assembly task types defined in the taxonomy (see section 4). The user can explore the different settings and preview the visualizations and customization settings. The settings can be stored to be reused and can be applied to the generated AR instructions.



Color selection
Main setup color Black
New Purple
Gear color Yellow
Animation ☑
Speed 5
Rotation Clockwise
Repeat ☑
Additional Info
Position TopLeft
Font size 12
Text color Black
Additional Info - critical steps
Position TopLeft
Font size 12
Text color Red

Fig. 5. Customization of visual elements in AR instructions

6. System Implementation

To realize the proposed systems, namely the authoring tool and the AR instructions generation application, Unity was used [21]. Unity is a software development platform that may target different end devices. The authoring tool may run on a PC, and it is compatible with a lot of 3D file formats (e.g., collada, .stl, .obj) that can be extracted by contemporary computer aided design software packages. The operation sequence is stored in a json file format, which is used for reloading old sequences in the tool, allowing the user to adapt them to new requirements and/or product variants, and as input for the developed AR application.

The AR application may target different end devices, including Android and Windows tablets, smart glasses and on Microsoft HoloLens 2. The latter has been the main testing device. This device is selected as it seamlessly supports advanced spatial mapping and hand tracking, while allowing the operators to see the instructions in their field of view. The combination of the two allows the application (given the correct input) to give the operator indications on where the part to be picked is and potentially even record that the operator has followed the correct points/ trajectory in other manual operations.

7. Validation Case

To validate how the proposed approach could fit into an industrial use case, it was applied in the assembly of a compressor. The goal of the validation is to follow the process from the instruction generation to their delivery in the shopfloor. The selected use case consists of a sequence of 18 assembly steps and one gluing step. This will allow the validation of both the algorithm for assembly sequence generation and the interfaces for defining the rest of the operations. The CAD files of the parts and the corresponding text instructions were provided by the manufacturer

At first, the authoring tool was used to automatically generate the assembly sequence. As there were multiple options for some part assembly direction, the engineer was called to select the optimal one. Moreover, the gluing step needed to be manually added. The user may select the base part and then identify the gluing trajectory (Fig. 3). A preview of the gluing instructions is shown to support the authoring tool user. The automatic generation of the majority of the instructions and the carefully designed interfaces facilitate the user to create the instructions in an agile way. After the instructions are prepared, the required details are exported to the AR application.

The operator is then using the AR application to complete the task. The instructions are visualized in the environment, while also guiding where each part should initially be. In the gluing task, the visualization's speed matches the actual speed that the operator should perform the task, as defined by the engineer in the authoring tool. As shown in 6 below, the instructions are accurately guiding the operator, providing the information required to support even inexperienced users. The use case provider has validated that the proposed approach can cover a wide aspect of manual operations and the generated instructions are easily perceivable by experienced operators. Moreover, the additional manual operations show the capacity of AR to move beyond just assembly tasks towards tackling complex processes, while also providing supportive information that reduce the margins for mistakes, leading to improved quality in the AR supported operations. The information visualization strategy currently includes detailed instructions in order to allow novice operators as well to perform the assembly tasks adequately. However, it is evident in literature that competence and skill-based models are being investigated in task allocation [22]. This investigation of matching competence and skill-based work instructions is set as a next step, given the fact that the required content is already provided by the developed authoring tool, and then selecting appropriate content that the end device should visualize, per skill level and also potentially connected with task repetition during the shift.

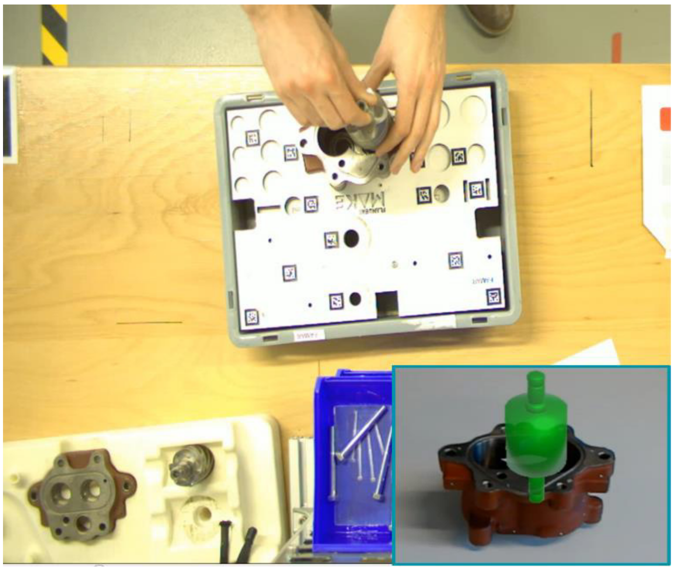


Fig. 6. The operator follows the AR instructions and assembles the part

8. Conclusion and Future Work

This study presents an authoring tool for facilitating the generation of AR instructions in manual operations. The authoring tool includes an approach for automated generation of instructions for the assembly operations, while it also allows the addition of other manual operations, such as gluing and surface treatment, which are common in production. The output of the tool is then used to generate AR instructions on the process, which are visualized in the operator's environment, making it more perceivable.

Future work on the proposed system will focus on the expansion of the capabilities of the authoring tool with the purpose of including more complex manual operations, such as packaging and quality inspection. Moreover, the authoring tool can be expanded towards enabling the re-utilization of the instructions in product variants. Lastly, future work on the generated AR instructions may allow content adaptation to the operator's experience and competency level.

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