

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

From Industry to Practice: Can Users Tackle Domain Tasks with Augmented Reality?

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CHALMERS UNIVERSITY OF TECHNOLOGY

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ABSTRACT

Augmented Reality (AR) is a cutting-edge interactive technology. While Virtual Reality (VR) is based on completely virtual and immersive environments, AR superimposes virtual objects onto the real world. The value of AR has been demonstrated and applied within numerous industrial application areas due to its capability of providing interactive interfaces of visualized digital content. AR can provide functional tools that support users in undertaking domain-related tasks, especially facilitating them in data visualization and interaction by jointly augmenting physical space and user perception. Making effective use of the advantages of AR, especially the ability which augment human vision to help users perform different domain-related tasks is the central part of my PhD research.

Industrial process tomography (IPT), as a non-intrusive and commonly-used imaging technique, has been effectively harnessed in many manufacturing components for inspections, monitoring, product quality control, and safety issues. IPT underpins and facilitates the extraction of qualitative and quantitative data regarding the related industrial processes, which is usually visualized in various ways for users to understand its nature, measure the critical process characteristics, and implement process control in a complete feedback network. The adoption of AR in benefiting IPT and its related fields is currently still scarce, resulting in a gap between AR technique and industrial applications. This thesis establishes a bridge between AR practitioners and IPT users by accomplishing four stages. First of these is a need-finding study of how IPT users can harness AR technique was developed. Second, a conceptualized AR framework, together with the implemented mobile AR application developed in an optical see-through (OST) head-mounted display (HMD) was proposed. Third, the complete approach for IPT users interacting with tomographic visualizations as well as the user study was investigated.

Based on the shared technologies from industry, we propose and examine an AR approach for visual search tasks providing visual hints, audio hints, and gaze-assisted instant post-task feedback as the fourth stage. The target case was a book-searching task, in which we aimed to explore the effect of the hints and

the feedback with two hypotheses: that both visual and audio hints can positively affect AR search tasks whilst the combination outperforms the individuals; that instant post-task feedback can positively affect AR search tasks. The proof-of-concept was demonstrated by an AR app in an HMD with a two-stage user evaluation. The first one was a pilot study (n=8) where the impact of the visual hint in benefiting search task performance was identified. The second was a comprehensive user study (n=96) consisting of two sub-studies, Study I (n=48) and Study II (n=48). Following quantitative and qualitative analysis, our results partially verified the first hypothesis and completely verified the second, enabling us to conclude that the synthesis of visual and audio hints conditionally improves AR search task efficiency when coupled with task feedback.

Keywords: Industrial Process Tomography, Augmented Reality, Human-centered Design, User Study, Qualitative and Quantitative Analysis

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LIST OF MAIN PUBLICATIONS

This thesis presents an introduction, summary and extension to the following appended main publications: papers I to V

- [I] Y. Zhang, A. Nowak, G. Rao, A. Romanowski, and M. Fjeld, “Is Industrial Tomography Ready for Augmented Reality? A Need-finding Study of How Augmented Reality Can Be Adopted by Industrial Tomography Experts”, in International Conference on Human-Computer Interaction (Springer, 2023, in press).
- [II] Y. Zhang, R. Yadav, A. Omrani, and M. Fjeld, “A Novel Augmented Reality System To Support Volumetric Visualization in Industrial Process Tomography”, in Proceedings of the 2021 Conference on Interfaces and Human Computer Interaction (2021), pp. 3–9.
- [III] Y. Zhang, A. Omrani, R. Yadav, and M. Fjeld, “Supporting Visualization Analysis in Industrial Process Tomography by Using Augmented Reality—A Case Study of an Industrial Microwave Drying System”, *Sensors* **21**, 6515 (2021).
- [IV] Y. Zhang, Y. Xuan, A. Omrani, R. Yadav, and M. Fjeld, “Playing with Data: An Augmented Reality Approach to Immersively Interact with Visualizations of Industrial Process Tomography”, in IFIP Conference on Human-Computer Interaction (Springer, 2023, **Under review**).
- [V] Y. Zhang, A. Nowak, X. Yueming, R. Andrzej, and F. Morten, “See or Hear? Exploring the Effect of Visual and Audio Hints and Gaze-assisted Task Feedback for Visual Search Tasks in Augmented Reality”, Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies 2023 (**Under review**).

We always refer to these publications in the thesis as papers I, II, III, IV, and V, according to the labeling in the list above.

SPECIFICATION OF MY CONTRIBUTIONS TO THE APPENDED MAIN PUBLICATIONS — PAPERS I TO V INCLUDED IN THE THESIS

- I Led and directed the work included in this paper. Finished the survey study with data collection and analysis. Have written most of the paper with feedback from my co-authors.
- II Led and directed the work included in this paper. Finished the conceptualization, mobile app development, and data analysis. Have written most of the paper with feedback from my co-authors.
- III Led and directed the work included in this paper. Finished the conceptualization, mobile app development, and data analysis. Have written at least 70% of the paper together with my co-authors.
- IV Led and directed the work included in this paper. Finished the conceptualization, reasoning, experimental design, user study implementation, and data analysis. Have written at least 90% of the paper together with my co-authors.
- V Led and directed the work included in this paper. Finished the conceptualization, reasoning, experimental design, user study implementation, and data analysis. Have written at least 90% of the paper together with my co-authors.

LIST OF OTHER PUBLICATIONS

- [1] Y. Zhang, M. Fjeld, M. Fratarcangeli, A. Said, and S. Zhao, “Affective Colormap Design for Accurate Visual Comprehension in Industrial Tomography”, *Sensors* **21**, 4766 (2021).
- [2] A. Nowak, Y. Zhang, A. Romanowski, and M. Fjeld, “Augmented Reality with Industrial Process Tomography: To Support Complex Data Analysis in 3D Space”, in *Adjunct Proceedings of the 2021 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2021 ACM International Symposium on Wearable Computers* (2021).
- [3] Y. Zhang, A. Nowak, A. Romanowski, and M. Fjeld, “An Initial Exploration of Visual Cues in Head-mounted Display Augmented Reality for Book Searching”, in *Proceedings of the 21st International Conference on Mobile and Ubiquitous Multimedia* (2022).
- [4] Y. Zhang, A. Nowak, A. Romanowski, and M. Fjeld, “On-site or Remote Working?: An Initial Solution on How COVID-19 Pandemic May Impact Augmented Reality Users”, in *Proceedings of the 2022 International Conference on Advanced Visual Interfaces* (2022), pp. 1–3.

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1 Introduction

The main work presented in this thesis first focuses on investigating how augmented reality (AR) can help the domain users in specific industrial processes monitored by industrial process tomography (IPT). Second, by sharing the same technique, it also identifies the capability of AR in improving practical visual search task performance with gaze assistance. This thesis illustrates the research done in the appended papers I to V, regarding the initial adoption of AR techniques for IPT and practical task performing with respect to four stages: need-finding of how AR can be used by IPT experts; AR framework conceptualization and mobile realization; the complete AR approach with evaluation; and the practical search task performing exploration.

In each paper, the research questions and the contributions are elicited and generated. Tables 1.1 and 1.2 give an overview of the specification of the papers I to V which constitute the main content of this thesis.

This thesis is summarized as follows and shown in Figure 1.1. First, Chapter 1 gives a preliminary overview of the research as well as the structure presented in the thesis. Chapter 2 introduces the general background of each of the four stages. The related work and contemporary research regarding each specific field is elaborated in Chapter 3. Chapter 4 illustrates the methodologies used and systems developed for each stage, as well as the results obtained correspondingly. Finally, discussions and conclusions with future work recommendations are presented in Chapters 5 and 6.

Table 1.1: *The research questions and research contributions listed in the papers I to V.*

Paper	Research Questions	Research Contributions
I	Could AR be used by IPT experts to effectively support process monitoring ?	1. Give an overview of the present status of using AR by IPT experts. 2. Identify the need of using AR by IPT experts to effectively support process monitoring. 3. Present the potential challenges in deploying AR in IPT
II	How can mobile AR support IPT users with volumetric visualization?	1. Propose an AR system in supporting collaborative analysis with interactivity and mobility for IPT. 2. Involve volumetric visualization regarding the IPT processes to support mutual collaboration of users.
III	How can mobile AR support IPT users for onsite analysis?	1. Propose an entire data processing and visualizing workflow of the IPT controlled industrial process. 2. Integrate AR technique to support IPT data visualization and on-site analysis for users.
IV	Can OST HMD AR facilitate IPT users for interaction and visualization analysis?	1. Pioneer a complete AR approach to help IPT users for contextual data visualization analysis by OST HMDs.

Table 1.2: *Cont.*

Paper	Research Questions	Research Contributions
V	How can hints and task feedback affect AR visual search task performance?	2. Provide immersive experience and interactive visualizations for users to interact and communicate with the IPT visualizations for better understandability, task performance and user experience. 3. Design and implement a comparative study to prove the effectiveness of the proposed AR approach compared to conventional methods and acquire early-stage feedback.
		1. Propose an AR approach supporting visual and audio hints, as well as gaze-assisted instant post-task feedback for visual search tasks. 2. Explore the effect of visual hints, audio hints, combined hints, and instant post-task feedback through gaze assistance on contextual AR searching. 3. Explore the effect of combining hints and task feedback in the same AR context.

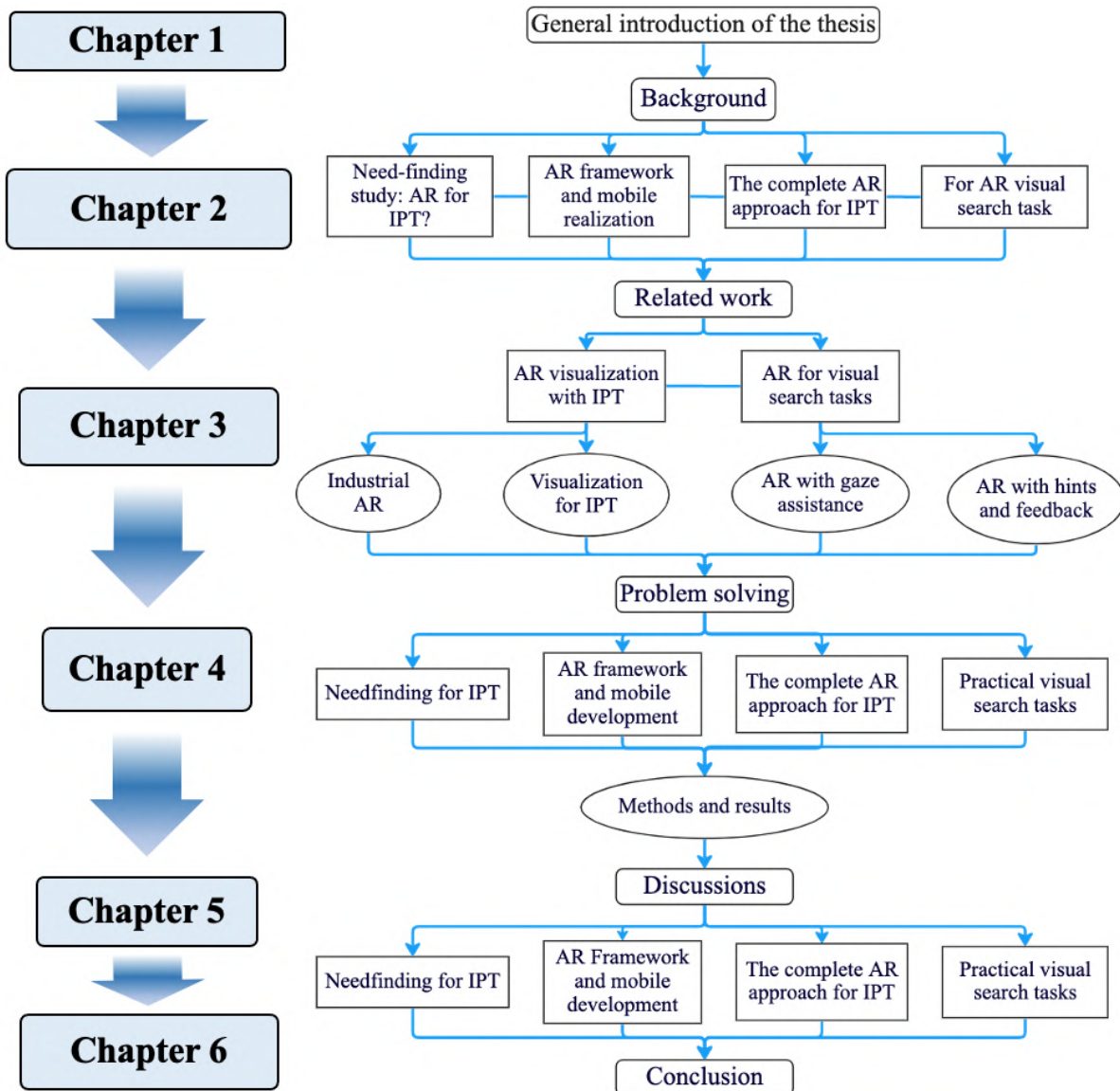


Figure 1.1: *Overview of this thesis.*

2 Background

This chapter gives a detailed overview of the relevant background within the context of this thesis, including the four stages mentioned above in the introduction.

2.1 Need-finding: Is AR Ready for IPT?

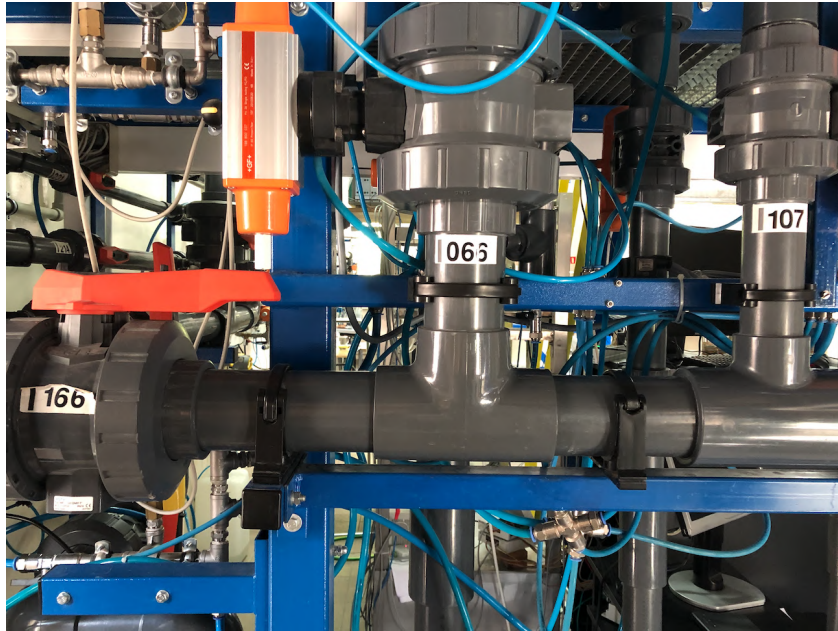


Figure 2.1: *The example scene of an IPT laboratory located at Lodz, Poland.*

IPT is a dedicated and non-invasive imaging technique which is pervasively used in manufacturing scenarios for process monitoring or integrated control[1–6]. It serves as an effective mechanism to extract complex data which is visualized in various representations and interprets it for domain users to comprehend the essence of the industrial processes [7–12]. An example view of an IPT working environment is shown in Figure 2.1. Due to the speciality and complexity of IPT, some rising technologies are therefore harnessed and made more accessible for all users - expert and lay - to perform complex tomographic data analysis to improve their productivity and efficiency. Some typical representatives of IPT, such as microwave tomography (MWT) [11, 13, 14], electrical resistance tomography (ERT) [15], and electrical capacitance tomography (ECT) [16] are widely used

for industrial purposes such as moisture detection [17, 18], crack detection and powder flow in pipes, and flow pattern detection of granules. This thesis specifically concentrates on a unique industrial microwave drying process [10] which uses precise drying and heating equipment for polymer foams with the aid of MWT. The targets of this drying process are firstly heating the object foam placed on the conveyor belt and then detecting the post-drying moisture distribution, by adopting the MWT technique.

While having some common points with Virtual Reality (VR), augmented reality/mixed reality (AR/MR) is an interactive technique where computer-generated perceptual information is visually superimposed on the real world [19–26]. Whereas in VR, a user interacts with virtual objects in a fully artificial three-dimensional world, in AR, a user’s view of the real environment is enhanced with virtual objects shown at the right time and position from the user’s perspective [27]. AR technology has been effectively deployed in various applications within industry due to its high mobility and interactivity. For example, AR can provide functional tools that support users when undertaking domain-related tasks such as data visualization and interaction because of its ability to jointly augment the physical space and the user’s perception [28, 29]. Taking devices and hardware as key parameters [19, 28], AR can be classified into three categories:

- **Head-Mounted Displays (HMD) and wearable hardware:** These devices can be further categorized into optical see-through and video see-through [20], displaying information inside the device while allowing users to see the surrounding real world.
- **Hand-Held Displays (HHD):** These are mobile screens, smartphones, or tablets with embedded camera and screen. The device fits within the user’s hands and can display virtual objects.
- **Spatial Augmented Reality (SAR):** These systems utilize digital projectors to display virtual information onto physical objects.

AR has successfully provided accessible and innovative solutions for various industrial application domains due to its capacity for interactive visualization through intelligent user interfaces[32]. Given its proven success within the automotive industry [33], shipbuilding [28], and robotics [29], our driving question is whether AR could also be useful in the domain of industrial tomography. The research question is thus elicited: Could AR effectively support process monitoring in industrial tomography? Both to capture the current status and to examine the potential of AR in this domain, we conducted a need-finding study in the form of a systematic survey to model the involved 14 participants. All were industrial tomography experts with at least three years of hands-on experience, whom we considered eligible to offer sufficiently in-depth insights and opinions.



Figure 2.2: *The three AR modalities presented to the participants. **A:** Head Mounted Display: These devices can be further categorized into optical see-through and video see-through [20], displaying information inside the device while allowing users to see the surrounding real world; **B:** Hand Held Display [30]: These are mobile screens, smartphones, or tablets with embedded camera and screen. The device fits within the user’s hands and can display virtual objects; **C:** Spatial Augmented Reality [31]: These systems utilize digital projectors to display virtual information onto the physical objects. A clear description of each modality was provided for our participants.*

2.2 AR Framework and Mobile Realization for IPT

After discovering the high potential of deploying AR/MR into the IPT domain from the need-finding process, we aimed to develop a realistic AR method for benefiting the relevant users. We identified that even though AR has been proved and applied in numerous fields such as medicine and education [34], due to deficiencies such as hardware limitation, poor computation power and low knowledge convertibility, it is still not a prevalent tool in most industrial application domains [19, 35]. Given that AR is capable of providing an interactive interface displaying digital content and offering ways to interact with information in a multimodal and collaborative manner [36], it has great potential to fill the gap between developers and IPT domain users by inciting novel mechanisms for onsite analysis. Hence, how to develop effective AR tools or systems which provide users with straightforward and comprehensible visualizations pertaining to the IPT process data becomes the central topic.

Visualization plays a dominant role in IPT-controlled industrial processes in that it can display the relevant data in an observation-friendly manner, which is then provided to domain users. The information related to the designated process, for example, a 2D graph of the tomographic spectrum or a 3D reconstruction of the voxel data, if collected and visualized instantly in a reasonable way, can help in better understanding of the process among the users [37]. Sophisticated data analysis always demands efficient reproduction of the measurement regarding the imaging process by IPT to uncover the material distribution inside the closed containers where the industrial process is executed [38]. As mentioned before, AR can provide functional tools that support users undertaking domain-related tasks, especially facilitating them in data visualization and interaction because

of its ability to jointly augment the physical space and the user's perception [28, 37]. Based on the interactivity and accessibility which AR can supply, we aim to explore the deeper usage of this technique in the IPT domain to support process data visualization and analysis.

In this stage, we introduce a novel and preliminary AR framework as well as the mobile realization to support interactive and collaborative onsite analysis regarding volumetric visualization in IPT. In our AR system, we are capable of providing users with an interactive way with high mobility to conduct visualization analysis alongside the ongoing industrial process. The necessary information is visualized in our mobile AR App which was built on iOS devices as an early-stage setup. Moreover, the proposed AR system incorporates multimodal visualizations used for characterizing the MWT processes, which opens the horizon of in-situ mutual collaboration of IPT related users.

2.3 The Complete AR Approach with Evaluation for IPT

As a representative human computer interaction technology, AR consolidates the interplay between digital objects and human subjects with much immersion based on a powerful and interactive AR visualization modality [39–41]. Such usage has still not become mainstream in most industries but a moderate number of research projects have successfully demonstrated its value in some cases [19]. With the rapid development of hardware technology, head-mounted display (HMD) AR has become widespread in many contexts since it enables interaction between digital information and human hands [42]. Under this circumstance, manipulation tasks that require interaction with the virtual objects can be achieved more accurately and quickly than when using conventional tangible interfaces [43, 44]. Optical see-through (OST) HMDs occupy the majority of contemporary AR contexts due to their ability to use optical elements to superimpose the real world with virtual augmentation [45]. This differs from video see-through AR where OST AR does not bear a component to process captured camera imagery [46]. With the ability of displaying manifold data in a more perceivable and interactive way [47, 48], applying AR to generate interactive visualizations for user-oriented tasks is often the preferred choice, and not only for industrial applications [49–53]. More specifically, it has been proven that OST AR can insert the virtual information into the physical environment with visual enhancement for human observers to control, thus improving the performance of information-dense domain tasks and further adding to its appeal to industrial practitioners [54, 55].

After the framework conceptualization and initial mobile AR realization, we propose the complete AR approach with practical user evaluation which (Figure 2.3.b and 2.3.c) allows users to easily observe and manipulate the IPT visualiza-

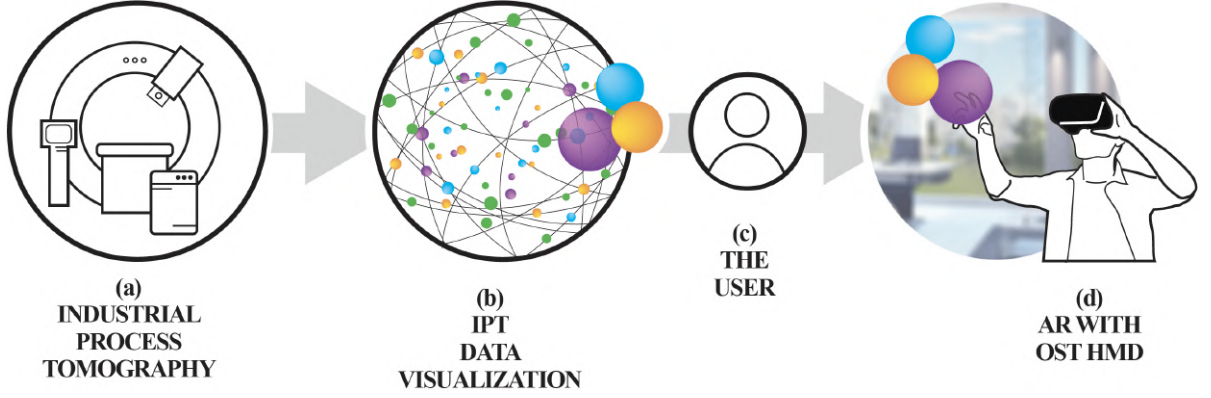


Figure 2.3: *Conceptualization of our proposed AR approach for IPT visualization analysis. a): The specialized IPT controlled industrial process is implemented in a confined environment. b): The IPT data visualizations originate from different processes. c): Users engage with relevant data analysis. d): User equipped with proposed AR environment by an OST HMD interacting with the visualizations for further analysis.*

tions with high immersion [56]. We propose deploying AR/MR applications to tackle the practical problems stemming from the specific area (interactive IPT visualization analysis). The main advantage of the proposed methodology is that it initiates, to our knowledge, the first mechanism for furnishing IPT users with immersive OST HMD AR with comparative evaluation to communicate with informative visualizations, using their hands for better comprehension of the designated industrial processes. The AR system employs Microsoft HoloLens 2, one of the representative OST HMDs (Figure 2.3.d), as the fundamental supplying equipment to create the AR/MR environments. The source data derived from the IPT supported industrial processes is always formidable to understand, so it needs straightforward and precise patterns to be visualized and interpreted. Our proposed approach provides a systematic framework which adopts accurate 2D/3D IPT data visualizations that are further used for interactive analysis to provide better understandability for domain users. We carried out a comparative study to demonstrate the superiority of our AR approach on bringing interactive visualization surroundings as well as eliciting better contextual awareness. We envision our AR approach to benefit areas where users deal with IPT visualization analysis.

2.4 Supporting AR Visual Search Tasks

Apart from the industrial domain, especially IPT, AR is endorsed and applied in facilitating task performance due to its capability of providing real-time interaction, as well as generating interactive interfaces of visualized digital content [57,

58]. Gaze assistance, in particular, has a promising role in AR applications owing to its easy, natural, and fast way of involving people in virtual environments [59]. Gaze-assisted techniques and implementations have been demonstrated to efficiently support AR applications by providing better user experiences (UX) [60] and more accurate target selection techniques [61]. People’s eye movements are easy to track, and gaze implicitly conveys what people are interested in. Thus, eye-tracking approaches are becoming more pervasive in interactive AR devices.

The search task in AR is a widespread research area which has received considerable attention, while its representations can be diverse, including visual element - [62], real world object - [63], or general searching [64, 65]. As a means to make the search process more accessible, it is even possible that HMD devices with the most advanced AR technology could soon become as ubiquitous as smartphones [66].

When performing particular tasks in the context of AR, hints can improve the ultimate task performance [67]. The type of hint, acting as a central and core tool, can vary. A widely-used tool is the visual hint, which is a mixture of graphical representations in AR with user interface (UI) actions associated with the physical world [68]. This effectively provides spatial and temporal guidance in AR. Another well-adopted hint is the audio hint, which presented as voice commands or directives can swiftly and clearly aid the user. A number of researchers have exploited audio hints for the purpose of informing, guiding, and directing within their designs [69, 70]. However, even though there is a substantial body of research into how visual and audio hints work in AR tasks, little has focused on search tasks other than exploring the combination of visual and audio hints in one AR framework.

Task feedback also matters. At present, there is almost no substantial research into this area. Task feedback is crucial for domain users to obtain better task performance in many situations related to AR [71, 72]. Here, we explore the effect of task feedback which is embodied as the playback of the human eye gaze recorded during the searching process. A vision-friendly colored dot smoothly following the path is used to display the eye trajectory (Figure 2.3.b). According to Vieira et al. [73], feedback has the potential to provide more specific information needed by the users in AR, which encouraged us to explore its potential influence in the same context.

In this stage, a complete AR approach for search tasks is proposed, examining the independent and the combined impact of visual and audio hints, and studying instant post-task feedback through gaze assistance [74]. We specifically concentrated on a book-searching task case, which includes all the essential components of a visual search procedure: visual environment, a particular object (the target book), and distractors (irrelevant books) [75].

3 Related Work

This chapter describes the relevant research related to the main work of this thesis. Specifically, it emphasizes the research status of harnessing AR/MR into IPT and how AR can affect practical search task performance.

3.1 AR Visualization with IPT

3.1.1 Industrial AR

There is a body of research to reflect the growing interest of the deployment of AR in various industrial applications. Cardoso et al. [19] wrote a systematic survey paper revealing the present status of industrial AR, where they concluded that most AR applications in the industry domain are incremental as they offer a different and more efficient way to convey information needed. Bruno et al. presented an AR application where industrial engineering data was visually superimposed on the real object that represents a spatial reference, where the exploration is more natural compared to traditional visualization software [76]. A recently published paper by Noghabaei et al. [77] indicated that the utilization of AR in architecture, engineering, and the construction industry had a significant increase from 2017 to 2018. More specifically, according to the powerful visualization functionality provided by AR, Lamas et al. [28] pointed out that AR could be used to visualize the 2D location of products and tools as well as hidden installation areas in the shipyard industry. Additionally, DePace et al. [29] found that AR can enhance a user's ability to understand the movement of mobile robots.

3.1.2 Visualization for IPT

Over a decade ago, Bruno et al. [76] developed an AR application named VTK4AR, featuring that functionality which uses AR to scientifically visualize industrial engineering data for potential manipulation of the dataset. The many requirements of applying AR within industrial applications have been summarized by Lorenz et al. [78] as they enumerated the user, technical, and environmental requirements. Mourtzis et al. [52] proposed a methodology to visualize and display industrial production scheduling and data monitoring by using AR, empowering people to supervise and interact with the incorporated components. In industrial manufacturing, a comparative study conducted by Alves et al. [53], demonstrated that

users who relied on AR based visualizations obtained better results in physical and mental demand in production assembly procedures. Even more specifically, Büttner et al. [79] identified that using in-situ projection based spatial AR resulted in a significantly shorter task completion time in industrial manual assembly. They designed two assisting systems and proved that the projection based AR outperformed HMD based AR in ease of use and helpfulness in their context. Avale et al. [80] proposed an adaptive AR system to visualize the industrial robotic faults through the HMD devices. They developed an adaptive modality where virtual metaphors were used for evoking robot faults, obtaining high effectiveness in empowering users to recognize contextual faults in less time. Satkowski et al. [81] investigated the influence of the physical environments on the 2D visualizations in AR, suggesting that the real world does not have a noticeable impact on the perception of AR visualizations.

Even though the volume of intersection research between AR and IPT is not substantial, other researchers have been investigating diverse pipelines of applying AR to generate interactive and effective visualizations for complex tomographic process data. Dating back to 2001, Mann et al. [82] exploited an AR application to visualize the solid-fluid mixture in a 5D way in stirred chemical reactors operated by one breed of IPT—electrical resistivity tomography (ERT). Recently, a new AR solution to visualize IPT data and further lead to collaborative analysis in remote locations was proposed by Nowak et al. [16]. More interestingly, their team also explored a more in-depth AR system with a more advanced prototype which created an entire 3D environment for users to interact with the information visualizations characterizing the workflow of IPT with high immersion [58]. The OST HMD AR was satisfactorily adopted in every experiment they conducted. Furthermore, Zhang et al. formulated a new system to generalize IPT within the context of AR, and directed a study where a novel AR framework was developed to support volumetric visualization of IPT, especially to yield high mobility for users [83].

3.2 AR for Visual Search Tasks

Search tasks are becoming more common in using AR because of the capability of projecting additional virtual information onto the physical environment. Contreras et al. [63] presented a mobile application with AR encapsulated to enable users to search for desired places, people, or events on a university campus. The superiority of AR lay in the fact that it offered certain visual elements that helped users to better locate the required result. Rafiq and his colleagues [84] proposed a dynamic AR framework to support an online book-searching task by using mobile augmented data. This framework also introduced a security layer which ensured the protection of sensitive cloud data. Gebhardt et al. [85] utilized gaze movement data to observe the MR object's label in a visual searching process through

a reinforcement learning method. Trepkowski et al. [86] presented a series of simulating experiments to investigate how visual search performance is affected by the field of view and information density in AR, indicating that the significant effect was aroused by these two factors. Van Dam et al. [87] studied the cues in a drone-based AR signal detection task but found no significant differences across AR cue types. Nevertheless, the effect of hints and task feedback continues to be more valued in AR visual searching.

3.2.1 AR with gaze assistance

Some research has already pioneered gaze-assisted UI to access more contextual information [88–91]. It has been shown that the optical see-through HMD which harnesses human gaze with eye-tracking as the interaction metaphor can contribute to efficient results [92]. Interestingly, there are some studies exploring eye-tracking to present menus to aircraft pilots, and to adjust their contents based on what the pilot is looking at [93]. In 2005, Curatu et al. [94] proposed a novel conceptualized system adding eye-tracking capabilities to a Head-Mounted Projection Display (HMPD), which was satisfyingly performed from a low-level optical configuration. Three years later, Park et al. [59] pioneered a system which includes a Wearable Augmented Reality System (WARS) to examine their proposition on an experiment in which they selected desirable items in an AR gallery with content mobility. Rivu et al. [66] successfully demonstrated the superiority of eye-tracking, showing that users are more positive in concentrating on their ongoing conversations when there is more gaze interactivity within AR environments. All the relevant research proved that the gaze assistance in AR activates improved perception.

3.2.2 AR with hints and feedback

Numerous researchers have endeavored to bring different modalities of hints into AR/XR systems as auxiliary tools for reaching desired results. Of these, visual hints [68, 95–98] and audio hints [69, 97, 99–101] are the two most common representations used. Arboleda et al. [102] presented augmented visual hints in a robot-involved AR system which aimed to enhance the visual space of the robot operator about the position of the robot gripper in the workspace, where the visual hints were used to improve distance perception and then the manipulation and grasping task performance. For tangible AR, White et al. [68] examined visual hints to enable discovery, learning, and completion of gestural interaction in a tangible environment. Seven visual hint types were generated: text, diagram, ghost, animation, ghost+animation, ghost+text, and ghost+text+animation. Two decades ago, Sawhney et al. [70] harnessed audio information to keep users of wearable devices updated with incoming messages and events. Lyons et al. [69] developed

an AR game system named "Guided by Voices", which equipped the user with a narrative sound clip that indicated the scenarios encountered and the correct steps to be taken for proceeding. Interestingly and more recently, Mulloni et al. [103] found that AR can be integrated with a mobile navigation system, while audio hints can be advisable for eye-free usage. Cidota et al. [104] compared the effects of automatic visual and audio notifications regarding workspace awareness in AR remote collaboration.

Although task feedback evaluation in AR has received little attention [105, 106] in the past years, a recent study carried out by Liu et al. [107] evaluated the influence of real-time task feedback in mobile handheld AR, which suggested that significant benefits will emerge if task feedback is engaged during the AR task. Zahiri et al. [108] studied real-time feedback in AR for supporting a surgical training, finding that most of the users preferred receiving the feedback while the task was being performed. Murakami et al. [109] found that haptic feedback as task evaluation can help users perform more effectively in a wearable AR system for virtual assembly tasks. Clemente et al. [72] demonstrated that continuous visual AR feedback can deliver effective information for the users in their sensorimotor control with a robotic hand, which has implications for amputee assistance in a clinical scenario. Even though some researchers have identified the effects of instant post-task feedback in gaze-interaction embodied virtual reality (VR) [110], its combination with AR is still scarce.

4 Problem Solving

This chapter gives a detailed description of the work done originated from the annexed papers, including the methodologies, experiment designs, and results obtained. As mentioned before, the main contribution of this thesis is first to bring the AR technique to the specialized IPT-controlled processes from zero to one, and then investigate the impact of AR in practical search task performing. For need-finding, we designed a survey study and conducted a qualitative analysis of the results. During the latter AR framework development and mobile AR implementation, the advantages of the AR method were identified and followed by the complete AR approach by OST HMD implementation with a within-subject user evaluation. For the practical search task, two modalities of AR hints and gaze-assisted task feedback were deployed within the OST HMD.

4.1 Need-finding: Is AR Ready for IPT?

Paper I aimed to identify the gap between AR and its successful deployment. More specifically, we sought to obtain the link between interactive visualization of AR and the effective working performance of the experts.

4.1.1 Method

To implement this proposition, we designed a survey study which included a number of objective questions and several subjective narration parts (25 questions in total), divided into three sections: **a general demographic section which included five questions** (age, gender, country of residence, place of work - industry or academia, and size of organization); **a visualization in tomography section with twelve questions**, (topics including years of experience, modalities of IPT and visualization techniques used in work along with their relevance and importance, and problems regarding visualization during daily work); and **a final part regarding AR with eight questions**, (topics including knowledge and experience with AR, recently involved projects, and possible usage with potential advantages and drawbacks of AR in the industrial tomography domain). In the final section, the three AR settings: HMD, HHD, and SAR were presented to the participants. All collected responses were anonymous.

We invited 14 participants from our Europe-wide project (<https://www.tomocon.eu/>) network to complete the survey. The working statuses of the participants

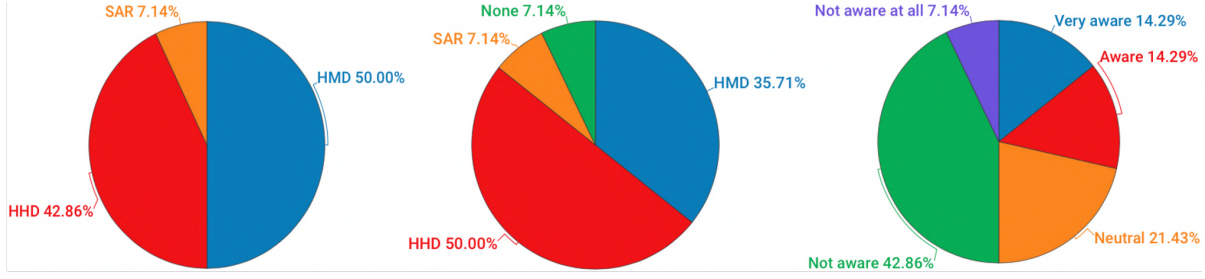


Figure 4.1: The answers of how domain experts responded to the current AR status. A: Q: Comfort: Which AR scenario shown above looks most comfortable for you? B: Q: Usability: Which AR scenario shown above looks most usable for you (might help with your work)? C: Q: Are you aware of any ongoing AR applications in industrial tomography?

were categorized into working in academia with tight collaboration of industry, working in industry, and working in both academia and industry. All were either experienced researchers or industrial practitioners distributed across Europe. Furthermore, all had distinguished skills in industrial tomography for at least four years while some were outstanding researchers in this domain. To mitigate undesired biases as well as to make our study more robust, we carried out a small pilot study followed by the formal study.

4.1.2 Results

Regarding the potential use of AR, even though most domain experts engaged in our study did not have much hands-on experience of working with AR, they still held a positive attitude regarding its potential usage in the context of industrial tomography after being exposed to the three AR modalities. They described the envisioned applications of AR from their own perspectives. We summarized their answers according to three aspects.

High accessibility. The majority of participants acknowledged the superior accessibility of AR for aiding domain experts. According to one expert involved in the study, AR, as a mobile tool, can make people concentrate on the targets more directly: *"It is very useful to have relevant information directly at the object of interest."* The accessible AR supports experts in different manners.

See-through capability. Simultaneously, these experts spotted the huge potential of utilizing AR within industrial tomographic processes. AR might become one effective tool to support task resolution. One expert came up with a comment regarding specific application cases: *"Especially if you deal with the case where there are opaque fluids which you cannot see, AR could be used as a powerful tool for interactive visualization."*

3D visualization ability. Another significant potential of adopting AR is its 3D visualization ability based on a few participants. The interactive 3D visu-

alization was seen to help with more precise task analytics.

From the responses obtained from these experienced domain experts, we looked into deploying the capability of AR in industrial tomography. The participants who were in favor of AR-tomography interplay claimed specific applications in terms of their hands-on projects. Most of them believed that AR could be unexpectedly beneficial for domain tasks pertaining to interactive visualization.

For the challenges to apply AR in industrial tomography, although most participants gave positive responses regarding its potential, we have to realize that AR is still not prevalent in most industries [19]. To uncover how to apply AR appropriately in industrial tomography as well as to understand its usability, we probed the latent challenges according to the participants' descriptions. These findings should be fully explored to situate AR properly within industrial tomography.

Ease of use. The most common challenge they posed was ease of use. Through the survey, participants gained a fundamental conception of AR but mostly questioned its ease of use. For example, some experts were reluctant to wear HMD AR for long-time inspection of a specialized process which would create unacceptable strain on human bodies: *"Yes, I think the headset is too difficult to wear for the industrial processes which have longer duration."; In many large reactors, the projection is possible. But for AR using head mounted display or other devices, it is difficult for hands-on operations and long time use."*

Speed and accuracy. Participants suggested that the speed and accuracy of AR may become a core problem in many application cases. One expert posed a more concrete appraisal: *"Industrial tomographic processes are often faster than human interaction and need automated control."* It is challenging for AR to make human interaction achieve the pace of industrial processes or to properly visualize vital information in the form of virtual elements.

Convertibility. AR is still rarely used in industrial tomography due to its unestablished reputation for suitably converting domain-related data into desirable visualizations. One researcher dealing with massive hands-on tomographic tasks remarked: *"From my point of view, converting the output from the tomographic sensor to properly represent output (i.e., moisture distribution) by AR can be challenging."* We have to realize that most domain experts lack the specialized knowledge of using AR devices, which is indispensable when adopting AR for visualization.

4.2 AR Framework and Mobile AR Development

Paper II and paper III concentrated on the theoretical AR framework conceptualization and actual mobile AR implementation based on the insights obtained from the need-finding study. Given that the IPT-controlled process in these two papers was an MWT for microwave drying which includes three phases—time-reversal imaging, post-imaging segmentation, and volumetric visualization, our

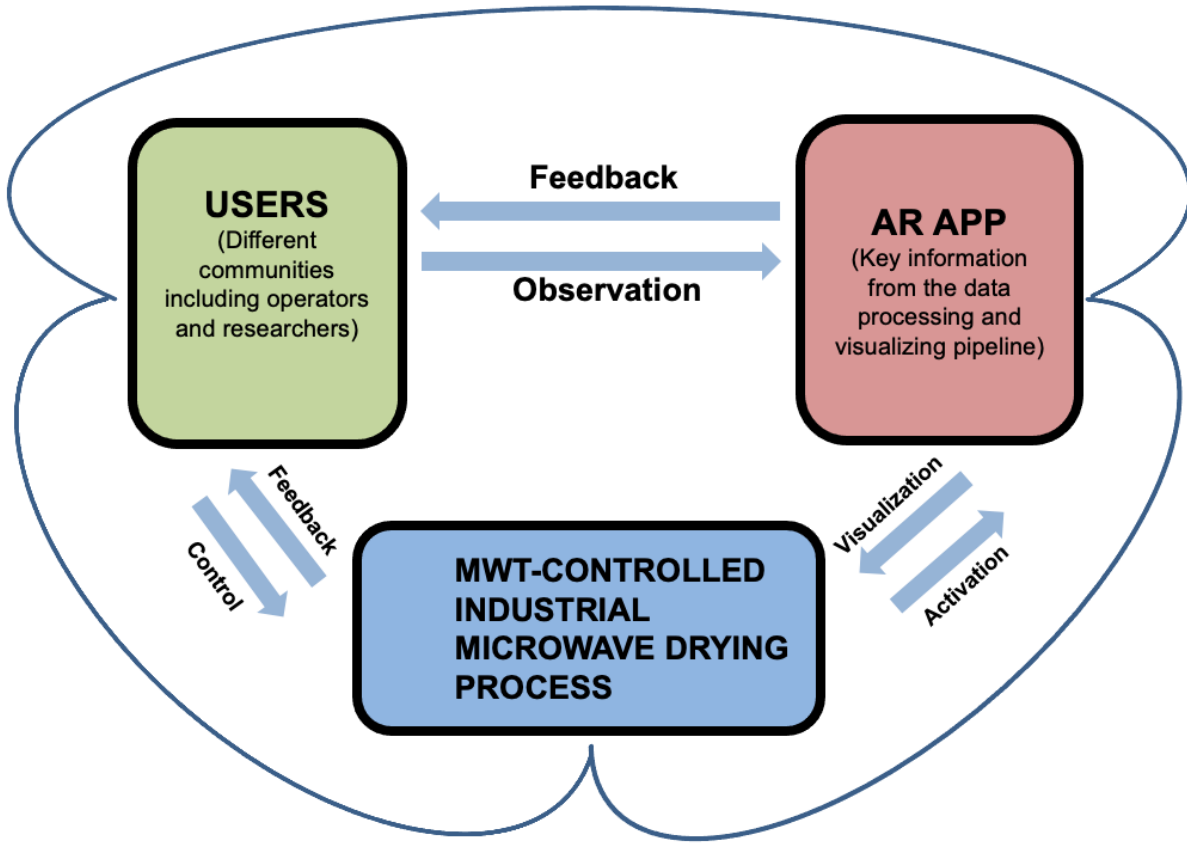


Figure 4.2: The conceptualization framework of the proposed AR system is: the MWT-controlled industrial microwave drying process block, which covers the whole running procedure of the process and provides data and elements used for analysis; users' block, representing the people involved in this context, such as operators who control and run the process and researchers who observe and analyze the process; the AR app block, which entails the AR implementation of a mobile AR app developed on the iOS/Android platform at the initial stage. [83, 111].

mobile AR app has incorporated the data from all of the three phases.

4.2.1 Method

To better support the onsite analysis related to the informative data processing and visualizing workflow, we present an AR framework which enhances the interactivity and immediacy of IPT data analysis. The proposed system has three main components, as displayed in Figure 4.2.

- MWT-controlled industrial microwave drying process: A unique heating and drying process operated in a confined chamber with sophisticated industrial settings. In our study, the target is a microwave drying process for polymer foams undergone by the precise HEPHAISTOS [17] microwave oven system.

- Users: Operators who control and run the drying equipment or researchers who take onsite observations and collect data for further analysis.
- AR app: The core part of our proposed system. As a preliminary stage, the application is manifested as a mobile app run in iOS/Android mobile devices and used for interactive and collaborative volumetric visualization and analysis. A multiple floating interface provided and overlaid in a real environment and containing information from our proposed data workflow is the main component of the application.

The principal part of the initiated AR system is a mobile app developed to visualize the necessary information revealed from the aforementioned data processing and visualizing pipeline, while it supports interactive and collaborative onsite data analysis. This app serves as an intermediary tool between the users and the precise experimental equipment used for displacing the visualized information regarding the ongoing process. The users, for example, operators, can interact with the visualizations projected on the AR interface, with the mobility of merely holding a mobile device alongside the bulky equipment. As Figure 4.3 illustrates, people from different communities, such as practical operators or academic researchers, have the capacity to interactively and instantly observe the information related to the process by simply activating the app without initiating other facilities. The app was developed via Unity and Vuforia engines, aiming at the present stage for iOS/Android portable devices such as smartphones and tablets. The app itself provides on-site multiple interfaces containing various visualizations obtained from the data pipeline. Users are able to switch to the visualizations they require for the desired analyses. As shown in Figure 4.3, some different floating interfaces incorporating different modalities of visualizations are presented and supported by switching after activating the app. The mobility of the AR interface provides users with ongoing visualizations as they move around the equipment that runs the designated process.

4.2.2 Results

The first concern was how to present a complete data processing pipeline with informative visualizations where these modalities are incorporated by the second focus – a preliminary AR framework to facilitate interactive and collaborative onsite data analysis regarding volumetric visualization in IPT systems. As a pioneer study in this related context, our proposed AR system opens a new horizon of deploying this interactive technique within IPT, boosting the complicated data processing and visualizing with an MWT-controlled microwave drying process. Based on our study, we present the following findings:

Interactivity. The most prominent advantage of this system is that the information visualization by the AR interface is completely interactive. By using

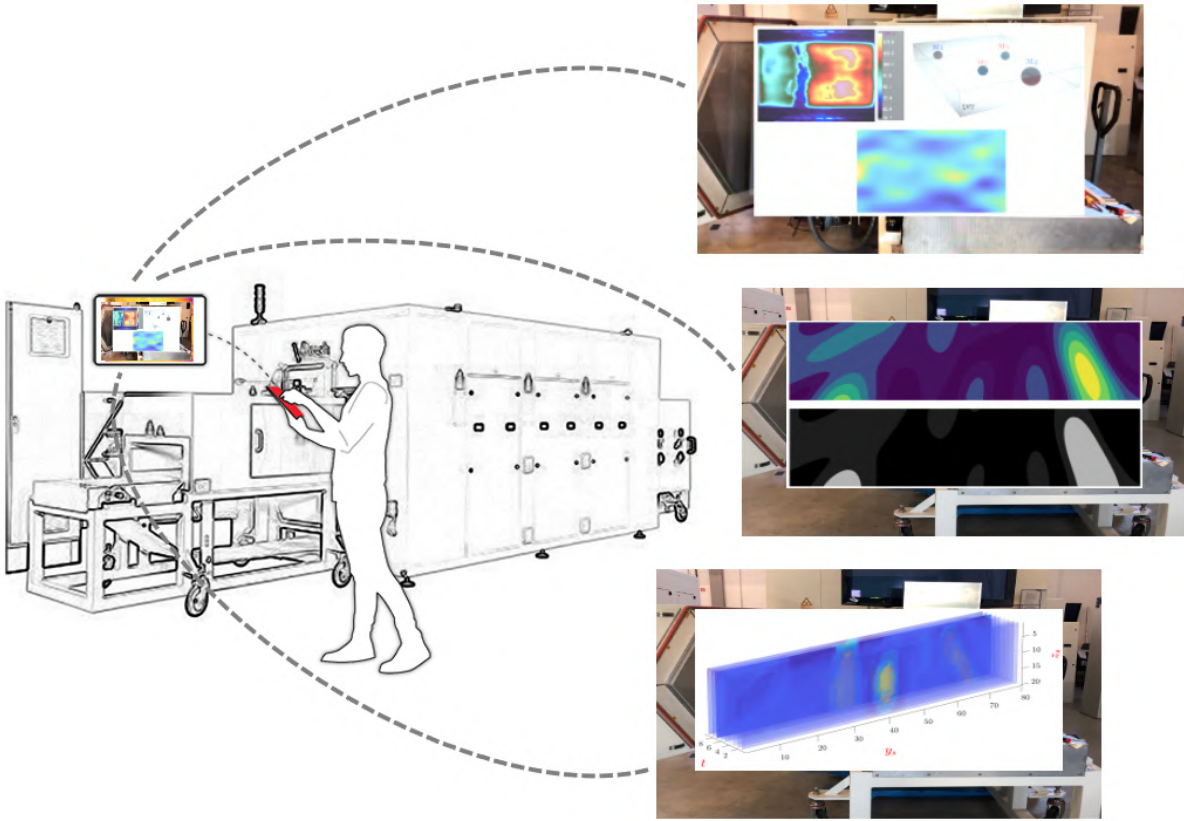


Figure 4.3: *The realization of the proposed AR system. Users hold the handheld smartphones/tablets to run the AR app alongside the industrial setting. After the app activation, users can then observe the visualizations displayed on the AR interfaces. At present, the app is supported via iOS/Android mobile devices. Users are empowered to switch to different visualizations regarding different phases of the process. The visualizations shown on the interfaces are multimodal, including the infrared image showing the condition of the process and the 3D/2D reconstruction of the MWT images (the upper left small figure on the floating interface in the upper right subfigure); the reconstructed MWT images with their segmented results to show the high moisture areas (the middle right subfigure); and the volumetric visualization (the bottom right subfigure) [111].*

the AR app after activation, a user can easily get instant access to the visualized data by observing the interface which incorporates the information needed for decision-making. Our AR system provides a new perspective of interactive data analysis to benefit IPT related users.

Mobility. Another strength of this system is its mobility. Generally, controlling and supervising an IPT related process requires implementation in specific and precise equipment and scientific laboratories. Researchers who observe the data and analyze the ongoing process invariably conduct this work in dedicated computers located at different places. However, with this system they are empowered to hold a portable mobile device (a smartphone or tablet) with a running

app to closely implement the data analysis while standing next to the precise equipment.

Information richness. The AR interface is used for displaying the most significant information needed for boosting the decision-making of the industrial process. We report the first AR application for bringing a complete data processing and visualizing workflow related to complex IPT process which contains the key information used for further analysis. For instance, a generated MWT image using a time-reversal technique is able to show the precise moisture distribution, while the up-to-date volumetric visualization has the capability to reveal the parameters of the drying material.

Mutual collaboration. Our system enables in-situ collaboration by providing a number of virtual AR interfaces comprising different information, including all the sophisticated visualizations emerging from the workflow. Under this setting, users from different communities such as hands-on operators, academic researchers, and engineers, can independently conduct visualization analysis by observing the corresponding visualizations, and interact with each other on common problems as well.

4.3 The Complete AR Approach

It is critical for users who intend to deal with IPT related analysis, regardless of their expertise, to fully understand the contextual information for in-depth visualization analysis. Paper IV advanced the whole AR pipeline and proposed a complete AR approach by the OST HMD for interacting with IPT data and tackling visualization analysis. A comparative user study was also implemented for evaluation.

4.3.1 Method

The contextual data used in this study was acquired from another microwave drying process for polymer materials monitored by MWT. This imaging modality was applied to detect the moisture levels and distribution of the polymer material through specific tomography imaging algorithms [112]. Three different visualizations were employed in this study from dissimilar MWT drying processes, including two in 3D and one in 2D; as 3D figures incorporate more information regarding the polymer materials used in the process. Different moisture levels were rendered with distinct colors and marked with different letters, denoting low moisture area, moderate moisture, the dry part, and the high moisture area respectively. The annotations were created based on the physical understanding by a domain expert.

A user study was conducted to find out whether our proposed AR approach, offering interactive and immersive experience for communicating with IPT visual-

izations, was superior to customary in-situ data analysis pertaining to supporting users' understandability and user experience. The main realization of this study was two different scenarios where the engaged participants encountered two different environments; our proposed AR approach to interact with the data representations with the aid of OST HMD; and the conventional setting using an ordinary computer with 2D screen and Matlab (only the visualization window was utilized for the experiment). Three tasks were designed towards IPT contextual visualization analysis for the participants to implement. We selected the within-subjects principle with the counterbalancing design principle [113]. The following hypotheses were made:

- **H1:** Our proposed AR approach can obtain better understandability for users compared to using the conventional setting.
- **H2:** Our proposed AR approach can contribute to a lower task completion time and fewer task errors.
- **H3:** Our proposed AR approach has better usability for users to interact with IPT data visualizations.
- **H4:** Our proposed AR approach has a greater recommendation level than the conventional setting.

Twenty participants (12 male, 8 female) aged between 24 and 41 ($M = 30.1$, $SD = 4.78$) were recruited by e-mail and personal invitations at a local university. All participants signed an informed consent at the beginning of each session, being aware of that there would be no personal information collected and that they could quit the study at any time. They were also told that the sessions would be audio-recorded, but all recordings would be treated confidentially and references would only be made in a purely anonymized form for scientific analysis. The participants had sufficient time to read the consent form and ask questions before signing it. Due to the complexity of IPT, the data generated is usually difficult to interpret by outsiders, even some of the experts. Hence, we started our study with a concise but detailed introduction about the study background, including the fundamental schematic of IPT, the source of the data visualizations, and the basic information about the visualizations used in this study. Before we began with the actual study sessions, we calibrated the Microsoft HoloLens glasses for each participant by helping them follow the instructions from the built-in calibration functional module. A short pre-training session was implemented to get the participants familiarized with and adapted to the HMD and the AR application used. The entire procedure of the user study is displayed in Figure 4.4.

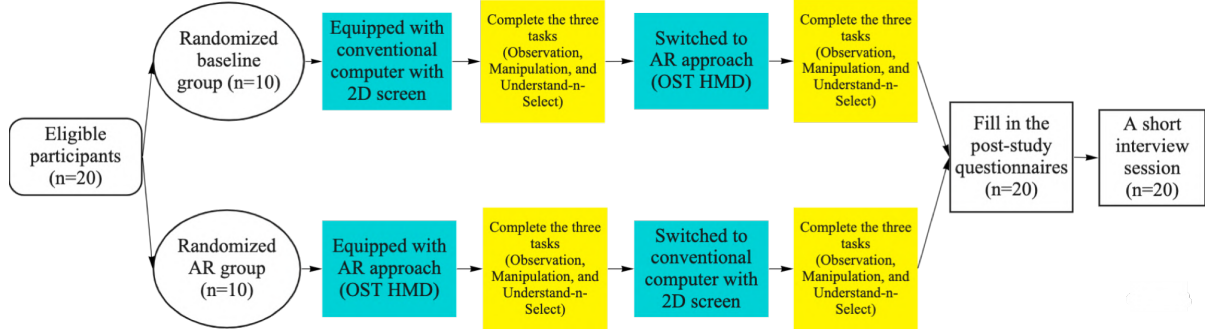


Figure 4.4: Flowchart of our user study with counterbalancing design.

4.3.2 Results

Qualitative Results: We compiled the results collected from the post interview sessions and real-time feedback of the participants during the study. The qualitative measurements generalized by a thematic analysis are presented in this section. The real-time feedback was conveyed spontaneously by the participants and recorded by the authors. For the post study interview, we asked the participants several subjective questions regarding what they liked and disliked about the tasks regarding our AR approach as well as the comparison between the two tested environmental settings. Concerning privacy and anonymity, we denoted the participants as P1 to P16 when recording the real-time feedback and encoding the interview answers. Based on the codes, we derived three themes: in-task understandability, interaction-based usability, and user experience.

Quantitative Results: In the following we present our quantitative measurements in relation to our hypotheses. The independent variables were identified as the two different environmental settings. From the study process and post-study questionnaire, five metrics – TCT, understandability, error rate, usability, and recommendation level – were employed as dependent variables. The TCT was merely measured from Understand-n-Select since this task is representative for practical IPT visualization analysis. To test the understandability, a 7-point Likert scale was adopted for participants to rate the level of the two environmental settings helping with understanding complex IPT data. The error was exclusively collected from the third task when users were supposed to select the designated areas. The largest number of errors was four in each environmental setting. Every error, if one occurred, was noted during the study and the error rate was thereby calculated by the authors. The system usability scale (SUS) [114] was harnessed to quantify the usability. We uniquely investigated the recommendation level by asking the participants the extent (the 7-point Likert scale) of recommending the two environmental settings. We statistically analyzed the collected results to identify any significance among the four metrics evaluated. Normality was checked as a prerequisite.

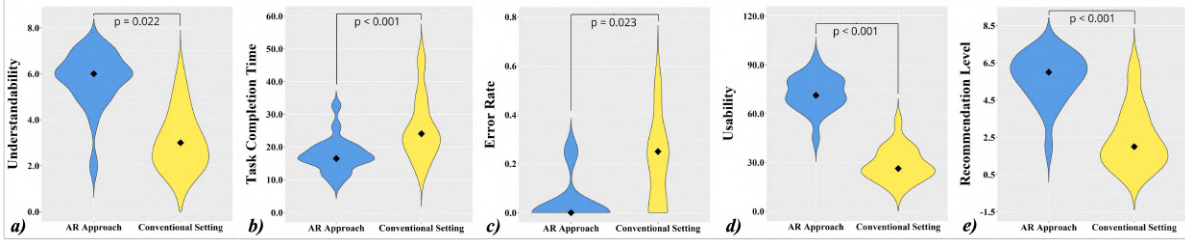


Figure 4.5: Statistical results between the AR approach and the conventional setting. a: The distribution of the understandability levels (1 to 7) rated by participants between the AR approach and the conventional setting. b: The distribution of task completion time (s). c: The distribution of the error rate (0.00 to 1.00). d: The distribution of the SUS scores representing usability (0 to 100). e: The distribution of the recommendation levels (1 to 7).

We conducted corresponding statistical analyses for those five metrics and significant differences were found in each of them as shown in Figure 4.5. Thus, we are confident to conclude that the four hypotheses have been well verified by the results.

4.4 Practical Visual Search Tasks

In paper V, to investigate how visual/audio hints and task feedback of AR can make a difference in facilitating the task performing for visual search tasks, we hypothesized:

- **H5:** Both visual and audio hints have a positive effect in facilitating AR searching performance and decreasing cognitive workload in AR, while the combination of these two hints has a greater effect than either does individually.
- **H6:** Instant post-task feedback has a positive effect for task performance and cognitive workload reduction in AR search tasks.

4.4.1 Method

Our proposed system, featuring an AR app used in OST HMD, is an interactive tool for users carrying out a book-searching task. The equipment kit consists of an OST HMD with built-in eye tracker which is responsible for recording the user's gaze during the task being conducted. There are two inter-correlated modules in our proposed system: the hints module and the instant post-task feedback module. The first module was designed to address **H5**, while the second targeted **H6**. The components – "User", "The AR app", and "Task completion" are commonly owned

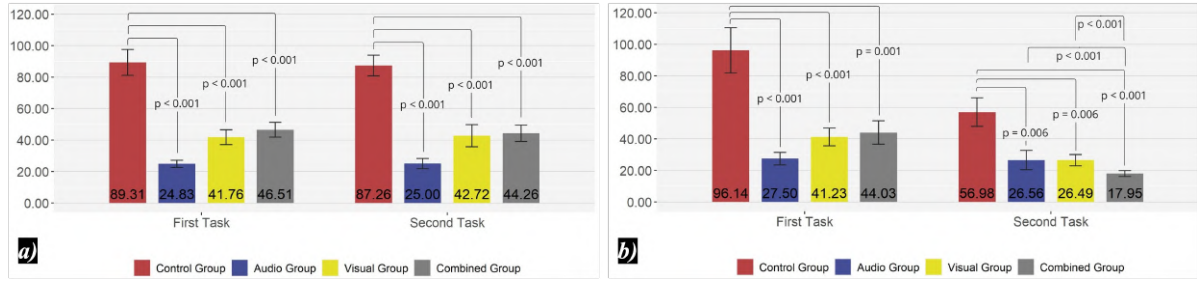


Figure 4.6: Study I (a) and Study II (b): The mean TCT (s) used per task by the four groups. Error bars show mean $\pm$ standard error (SE).

by the two modules. The AR app is the core of the system which bears the necessary information needed including hints and task feedback.

The book-searching case was chosen and implemented with the aid of the proposed AR approach. The AR app encoded a number of book titles which were used as the stimulus in the study. The user with an OST HMD with a real-time built in eye-tracker stood in front of the bookcase, where the task was to find a specific but randomly determined book (Figure 2.3.a) after activating the app. We chose arrows as the indicators, but showed them in an easily-recognizable color and in a static state. Since all virtual artifacts were displayed in the world space, users' movements did not affect an object's position. As shown in Figure 2.3.c, the bright-purple arrow visually helped the user to locate the target book. For audio hints, users received an audio instruction about the approximate location of the targeted book. The auditory information was presented as a clear and simple instructive voice message, allowing the users to finish the task with higher efficiency. The instant post-task feedback was provided as a visible playback of gaze recording. As shown in Figure 2.3.b, the user's gaze was denoted as a brightly colored dot following the trajectory. During the book-searching phase, gaze trajectories were marked and recorded. After one search task, users were able to watch their gaze playback of the trajectory, after which they proceeded to the next task.

A comprehensive comparative user study based on a between-subject with coupling within-subject factors was then designed. The independent variables were the tasks (within-subject) and the groups (between-subject). The study was comprised of two sub-studies (Study I and II) where the participants from Study II received the task feedback while those from Study I did not. Before starting the experiment, we conducted a pre-testing session where several people were invited to test the desired functionalities of the AR app. Some minor adjustments were then made to improve the visual and locational clarity, including the visual hint made into a more vision-friendly arrow and our testing environment moved to a more spacious and bright function room. The participants ($n=96$) were randomly sorted into four different groups in both Study I and II ($n=48$ in each): control,

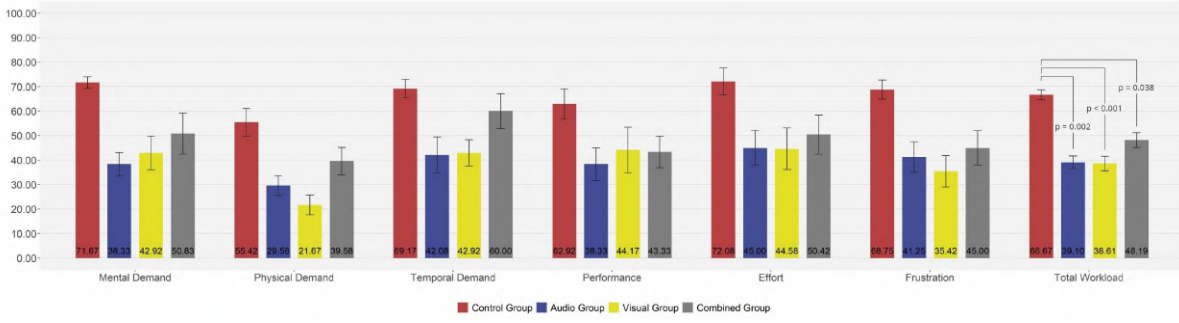


Figure 4.7: Study I: NASA TLX for the first task by the four groups. Error bars show mean $\pm$ standard error (SE).

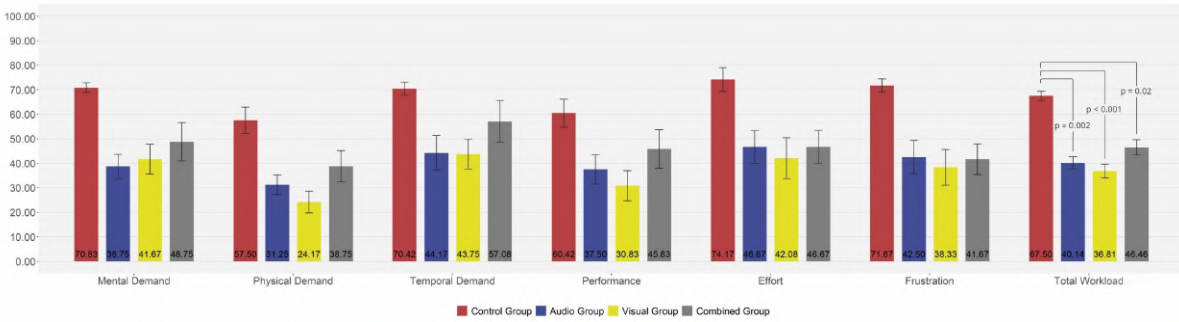


Figure 4.8: Study I: NASA TLX for the second task by the four groups. Error bars show mean $\pm$ standard error (SE).

audio, visual, and the combined groups (n=12 in each).

4.4.2 Results

The two metrics (dependent variables) employed for assessing the tasks were task completion time (TCT) and NASA Task Load Index (TLX) in both studies.

TCT in Study I: To identify the statistically significant differences of the results, a 2(task)*4(group) mixed analysis of variance (ANOVA)($p = 0.05$) was performed. This analysis was performed using IBM SPSS Statistics, as were the following statistical measurements. Bonferroni-corrected post hoc tests were employed to determine if the pairwise groups were significantly different. We found that all participants did not have statistically significant shorter TCT in the second task compared to the first, but there were significant main effects of the four groups on the TCT measured. No significant interaction was found between the tasks and the groups. The Bonferroni post hoc tests showed statistical significance between every pairwise comparison of the control group with all the other groups in both tasks.

NASA TLX in Study I: The study showed that all participants did not have a significantly different cognitive workload in the second task compared to

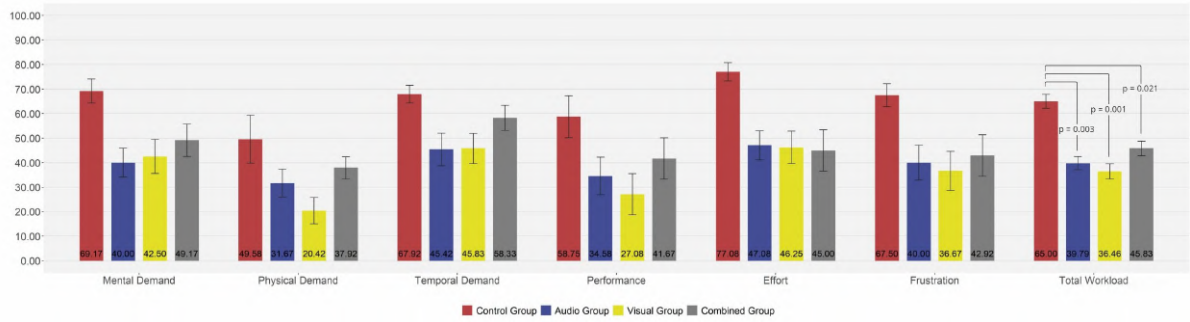


Figure 4.9: Study II: NASA TLX for the first task by the four groups. Error bars show mean $\pm$ standard error (SE).

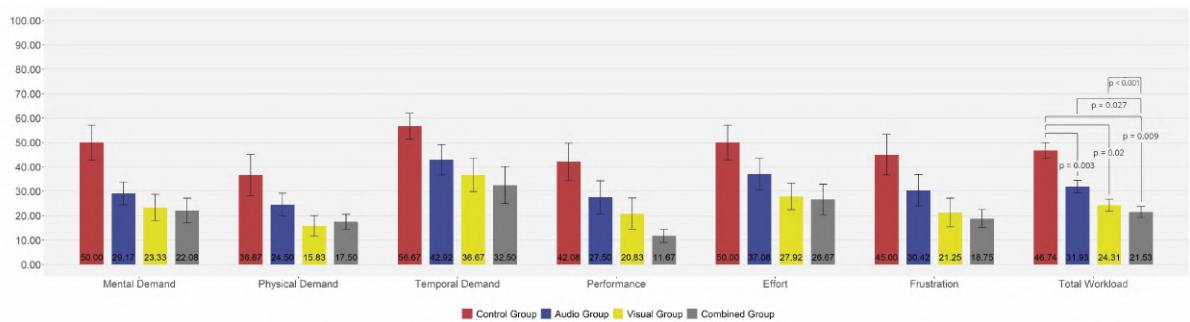


Figure 4.10: Study II: NASA TLX for the second task by the four groups. Error bars show mean $\pm$ standard error (SE).

the first. The post hoc test showed all three groups were significantly different when compared to the control group in the first task. In the second task, the control group had statistical significance between the other three groups. Again, no significant differences between every pairwise comparison of audio, visual, and combined groups were found in both tasks in Study I.

TCT in Study II: All participants had statistically significantly shorter TCTs in the second task compared to the first. The results also showed significant main effects of the four groups on the measured TCT. In addition, there was a significant interaction between the tasks and the groups. The Bonferroni post hoc tests showed statistically significant differences between every pairwise comparison of the control group with all the other groups in the first task. Likewise, the second task also showed significant differences between the control group and the other three groups. However, we found that the pairs of the audio-combined and the visual-combined had statistical significance as well. The TCT of the combined group was statistically different from the other three groups in the second task.

NASA TLX in Study II: All participants had a statistically significantly lesser cognitive workload in the second task compared to the first. There were significant main effects of the NASA TLX results among the four groups, but no significant difference was found on the interaction between the tasks and the

groups. For pairwise comparison, the post hoc test showed no significant differences between every pairwise comparison of audio, visual, and combined groups in the first task. However, all the other three groups were significantly different when compared to the control group. In the second task, the participants from the control group still possessed significantly more cognitive workload compared to members of the other three. Nonetheless, the pairs of the audio-combined and the visual-combined also revealed significant differences. The result means the synthesis of the two modalities of the hints we tested worked better than when there was only one modal hint in the second task, where the gaze playback was provided as the task feedback in the same context.

5 Discussions

In this chapter, the insights obtained with the limitation identified regarding the four stages are described.

5.1 Need-finding

AR has become a renowned concept and technique with the rapid development of mobile smart devices especially the successful usage in industrial applications. Distinct from [77] (specialized in understanding VR/AR in design and construction) and [19] (specialized in evaluating AR in industries), we specifically focused on exploring AR in the domain of industrial tomography to resolve research question I.

We found that for IPT experts, visualization is a critical inclusion of their daily work, especially 3D visualization which triggered the most difficulties. We sought to dig out more about the prospects, especially in terms of data-driven and machine learning-driven applications [115]. According to our surveyed participants, HMD and HHD AR were considered to be favorable modalities which were able to bring comfort and effectiveness to benefit industrial tomography. Notably, almost all of our participants expressed a positive attitude towards the potential usage of AR due to its promising functionality such as interactivity and providing an extra platform for 3D visualization.

At this stage, there still exist limitations of our study. One limitation is that our study was done exclusively from the perspectives of a specific group of experts in IPT. Furthermore, we surveyed 14 Europe-wide participants, which is only a small sample of the domain practitioners. A larger number of samples would contribute more rigorous and persuasive conclusions. Last but not least, we did not control all the influential factors of the survey, such as the time length of the survey, which might affect the answers obtained.

5.2 AR Framework and Mobile Implementation

To tackle research questions II and III, we entered the second stage of this thesis. The first concern of this stage is to present a complete data processing pipeline with informative visualizations, while these modalities are incorporated by the

second concern – a preliminary AR framework to facilitate interactive and collaborative onsite data analysis regarding volumetric visualization in IPT systems. As a pioneer study in this context, our proposed AR system, especially the developed mobile AR app as the third concern, opens a new horizon of deploying this interactive technique into IPT, boosting the complicated data processing and visualizing with an MWT-controlled microwave drying process.

We noticed that there are some deficiencies in this preliminary AR framework supporting the visualization of data workflow. Foremost, the dataflow itself does not include all the necessary information related to the MWT-controlled process. Moreover, although we have set a precedent for bringing the AR technique to benefit IPT especially in complex visualization analysis, we have not yet evaluated our method through a systematic user study to gain constructive and critical feedback. In addition, our preliminary AR framework is embodied as a mobile app on portable smartphones or tablets. It limits the AR interface to small, bounded screens. The formulation of AR in handheld mobile devices to some extent hinders the essential advantages of AR, which should be tackled by introducing more advanced headsets that can make AR scenes more interactive and immersive.

5.3 The Complete AR Approach with Evaluation

We then developed the complete AR approach with OST HMD for IPT data visualizations to fill the gap between AR technique and the IPT context to answer research question IV. The practical realization was achieved by an AR app supported in Microsoft HoloLens 2; a typical OST HMD which provides immersive interaction for users to communicate with the multiple visualizations. To evaluate our proof-of-concept, a within-subject user study with counterbalancing design was implemented based on 20 recruited participants in order to justify the hypothetical superiority of the proposed AR approach compared to conventional computers with 2D screen for IPT data visualization analysis. Our approach offers a complete conceptualization with the realization of an immersive AR method with the aid of OST HMD towards IPT. Our participants were highly favorable towards its interactive features. While no previous work emphasized this, we structured a systematic AR framework with high interaction capabilities for IPT users.

Another important property to be realized is the ubiquity and knowledge transferability of the proposed AR approach. As most of the participants had little experience in IPT, we are therefore encouraged about the potential for our method to bring outsiders to this specialized technique for domain supporting. Additionally, although the data used in this study was generated merely from MWT, the diverse genres of IPT have high transferability since they comply with similar mechanisms [83]. It is fair to say that the superiority revealed in our AR approach is highly transferable to different genres of IPT.

For limitations at this stage, the virtual buttons for switching different figures in the AR application were reported as not sensitive enough. Also, although hand gestures in AR space are intuitive and highly close to what people commonly do in physical reality, some participants reported a tiny difficulty when the app was initiated. In addition, we admit that the experiment itself and the contextual IPT data were monotonous and small scale. Last but not least, the stimuli discussed in this paper had only three visualizations derived from different industrial processes supervised by the specific MWT, which lacks diversity. More manifold data from other genres of IPT could be examined to make the results more robust.

5.4 Practical Visual Search Tasks

The final stage was intended to respond to research question V. What did we do and achieve in this stage? By sharing the same technique from previous stages and being inspired by it, we identified the effects of visual/audio hints in either single or combined setups, together with instant post-task feedback for AR search tasks. We developed an AR approach engaging two modules of the hints and gaze-assisted task feedback separately with the aid of Microsoft HoloLens 2. A case study for a visual book-searching task was chosen. Then, a comprehensive user study was designed, where 96 participants were allocated in Study I ($n=48$) and Study II ($n=48$) and placed randomly into four groups (control ($n=12$), audio ($n=12$), visual ($n=12$), and combined ($n=12$)) in each sub-study. The user study was based on the between-subject principle with within-subject factor.

Our proposed solution has proved to be advantageous for increasing AR search task performance and simultaneously reducing the cognitive workload on users. The noticeable decrease of TCT and the cognitive task workload was a confirmation of our hypotheses. We also believe the research implication of our study has high generalizability and convertibility to benefit the general AR searching specialization.

The limitations should be admitted as well. First, we designed two visual book-searching tasks to be performed using two bookcases that contained different books, eliminating memory as a factor in the second task. The thickness and order of the books might alter the participants' search speeds and workload. Also, the sample size of our study might not be sufficient. In addition, due to the performance sequence, the gaze review only influenced the second task in our study. However, in order to better understand the influence of gaze review on search tasks, there could be another design solution with a counterbalancing factor [113] where the gaze playback can be recorded from the second task then used for the first task.

6 Conclusion

To answer the question raised in our thesis title, we are able to say that AR can be used to aid users for tackling domain tasks in both IPT and practice. To bring the AR technique to the specialized IPT field yields a lot of difficulties. As a specialized area, IPT has its particular and traditional mechanisms to deal with domain tasks, where opportunities exist for cutting-edge AR to be imported to fill certain gaps. In this thesis, we developed and implemented usable stages to harness AR within IPT to benefit domain users.

First, we investigated how IPT experts can effectively work with AR by means of modeling users through a systematic survey. We designed a logically-consistent survey study, recruited 14 domain experts with relevant disciplinary backgrounds, then carried out both a pilot study and a formal study. We displayed the current status of the use of AR in IPT and explored the high potential of adopting AR more in the future owing to the superiority of interactive visualization. Second, we proposed an initial AR framework including a complete data processing and visualizing workflow in an IPT system. The overall realization of this AR framework was conducted by a mobile AR App run on smartphones/tablets, aiding a specific MWT controlled microwave drying process. We successfully proved that this novel system brings new conceptualization in this domain by offering interactivity and mobility on users' in-situ data analysis and visualizations. In the final stage of our industrial context, we proposed a complete AR approach with OST HMD for users to immersively interact with the specific IPT data visualizations for contextual understanding and task performing. The increased understandability, reduced TCT, lower error rate, greater usability, and higher recommendation level of the methodology have been reflected in our work. A within-subject user study demonstrated the superiority of the proposed AR approach over the current standard IPT visualization analytical environment and proved that immersion in 3D AR outperforms conventional 2D screen computers in enhancing contextual understanding and user experience.

Regarding practical domain task performance, we have described an AR approach for visual search tasks with supported visual/audio hints and gaze-assisted instant post-task feedback. Based on our hypotheses, we designed and conducted a case study of visual book-searching where the gaze playback acted as instant post-task feedback. The experimental procedure consisted of a comprehensive user study (n=96) with two comparative sub-studies. The resulting analysis was based mainly on collected NASA TLX answers with TCT measurements as preliminary

analytic metrics. We found that both visual and audio hints have a positive effect in facilitating task performance and the combination of the two hints works better than either individually, under the condition that there is instant post-task feedback. We pointed out the high generalizability and convertibility of our research output in taking advantage of general AR searching processes.

For future work, we will firstly concentrate on upgrading the AR app by improving the touch sensitivity of the virtual buttons on the interface as well as eliciting more early guidance for users to better start with the app. In addition, another concern will be to increase the experimental diversity by, for instance, involving a larger number of participants from different communities including both experts and outsiders and adding more nonidentical experiments with distinct design principles. Last but not least, integrating AR (HMD or mobile devices) with intelligent UIs manifesting various visualizations or visual analytics regarding the specific IPT processes can broaden the horizon of the relevant stakeholders. Our work benchmarks the intersection between OST HMD AR and the IPT domain to highlight the future direction of bringing more related and advanced techniques into different industrial scenarios. We hope our research will lead to better strategic design within this context and bring more interdisciplinary novelty to Industry 4.0 [116].

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