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Developing augmented reality capabilities for industry 4.0 small enterprises: Lessons learnt from a content authoring case study

Katherine van Lopik*, Murray Sinclair, Richard Sharpe, Paul Conway, Andrew West

Wolfson School of Mechanical Electrical and Manufacturing Engineering, Loughborough University, Loughborough, LE113TU, United Kingdom

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ABSTRACT

Augmented reality (AR) has been proposed as a disruptive and enabling technology within the Industry 4.0 manufacturing paradigm. The complexity of the AR content creation process results in an inability for Small Enterprise (SE) to create bespoke, flexible AR training support "in-house" and is a potential barrier to industrial adoption of AR. Presently, AR content creation requires a range of specialist knowledge (e.g. 3D modelling, interface design, programming and spatial tracking) and may involve infrastructure changes (e.g. fiducial markers, cameras) and disruption to workflow. The research reported in this paper concerns the development and deployment of an Augmented Repair Training Application (ARTA); a template-based interface to support end user (shop floor) AR content creation. The proposed methodology and implementation are discussed and evaluated in a real-world industrial case study in collaboration with a Small Enterprise (SE) in the Used and Waste Electronic and Electrical Equipment sector (UEEE/WEEE). The need for end user friendly templates is presented in the conclusion alongside further related work.

1. Introduction

The term Augmented Reality (AR) has been defined as a system which "supplements the real world with virtual (computer-generated) objects that appear to coexist in the same space as the real world" (Azuma et al., 2001). Although not a new concept (e.g. see (Caudell and Mizell, 1992)), technological advancement including increased computational power, cost reduction and miniaturisation have resulted in a resurgence of AR use. The use of AR within *industrial applications* is the focus of the present study, however the benefits of AR use for knowledge sharing can be found in a variety of domains including *tourism* (Loureiro et al., 2020), *entertainment* (Niantic Inc and Nintendo Inc, 2019), *education* (Arici et al., 2019), *medicine* (Eckert et al., 2019) and the changeable environments and tasks encountered within the Industry 4.0 paradigm (Bottani and Vignali, 2018), see Fig. 1.

The value adding potential of AR applies to both *external* (e.g. customer engagement, marketing) and *internal* enterprise activities (e.g. design, collaboration and process efficiency) (Mourtzis et al., 2017; Rauschnabel et al., 2019). The use of AR as a knowledge sharing tool will help enterprises transition from a siloed resource based view (RBV) where the rare, inimitable and non-substitutable are valued, to more versatile resources supporting system flexibility and improved business growth (Nason and Wiklund, 2018). Within industrial settings, AR has been identified as a suitable method to share expert knowledge, e.g. remote tutelage (Koiwai et al., 2016; Lazaro, 2017; Ruppert et al., 2018), flexible access to system data (Ruppert et al., 2018) and the digitisation of siloed information found offline in manuals and tacit knowledge (Hao and Helo, 2017; Renner and Pfeiffer, 2017).

Industry 4.0 (I4.0), the "digital twin" and Human-Cyber-Physical Systems (HCPSs) are next generation manufacturing paradigms for system optimisation and waste reduction (Kagermann et al., 2013; Moeuf et al., 2018). The use of Artificial Intelligence, Big Data and Machine Learning (Duan et al., 2019) and human agility results in systems that are flexible but increasingly complex (Kagermann et al., 2013). There is a need for accuracy within the twin roles of *knowledge capture* (e.g. tracking and recording processes as they occur) and *knowledge dissemination* (e.g. education, training, reminding) to support effective teamworking within the digital twin human and cyber components. To mitigate potential slippage or migration of processes, particularly as time passes, AR may perform an essential role in the accurate capture and dissemination of knowledge by ameliorating discrepancies between a *process-as-designed* and a *process-as-performed*, providing training and prompting to ensure processes are compliant with business goals, illustrated in Fig. 2.

Visual AR provides contextualised data in the users sight line via devices such as handheld displays or "in-sight" "Augmented Real-

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* Corresponding author.
E-mail addresses: k.van-lopik@lboro.ac.uk (K. van Lopik), m.a.sinclair@lboro.ac.uk (M. Sinclair), r.g.sharpe@lboro.ac.uk (R. Sharpe), p.p.conway@lboro.ac.uk (P. Conway), a.a.west@lboro.ac.uk (A. West).

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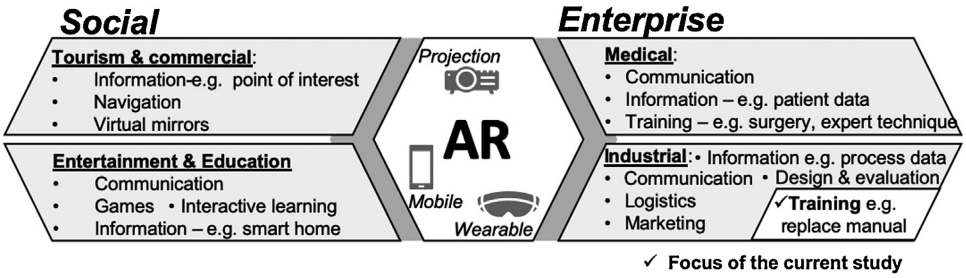


Fig. 1. Applications and use of augmented reality within social and commercial settings.

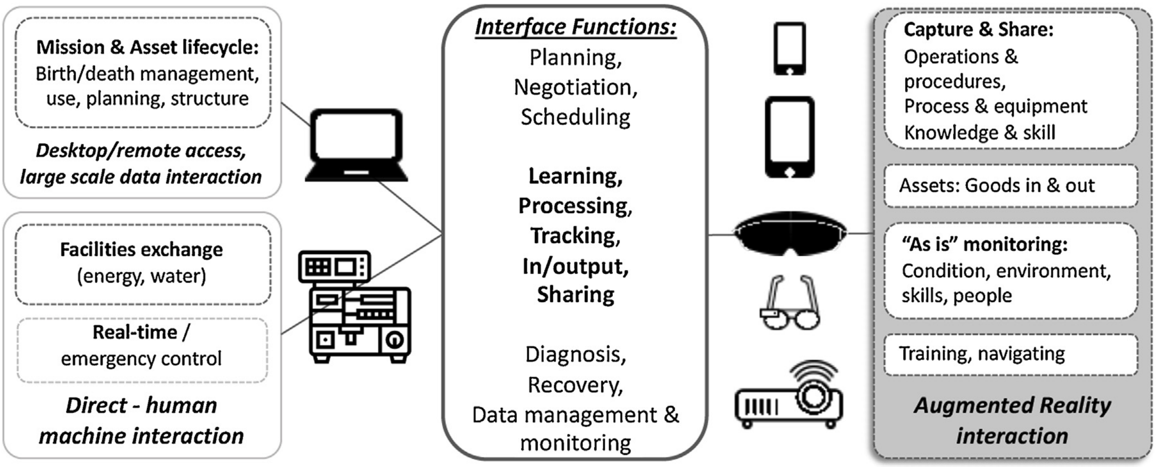


Fig. 2. The tasks on the right are concerned with data acquisition, daily interaction and knowledge capture/ share within dynamic environments where workers need to be mobile.

ity Smart Glasses" (ARSGs (Ro et al., 2018)). The hands free nature of ARSGs is particularly suited to "hands busy" tasks such as maintenance, repair and assembly (Palmarini et al., 2018). Although the potential benefits are widely recognised (e.g. (Koiwai et al., 2016; Lazaro, 2017; del Amoa et al., 2018; Palmarini et al., 2018) there are numerous barriers to adoption of AR within industry including ergonomic, technical and privacy concerns (Ro et al., 2018). Ergonomic and technical issues (e.g. device weight, eye strain, wearable hygiene and battery life) may diminish over time with the evolution of lighter weight hardware (e.g. HoloLens 2 (Microsoft, 2019)) and adaptive technology (e.g. Magic Leap One (MagicLeap, 2019)). Privacy concerns, such as recording of worker activity, may be reduced through changes to legislation and by adopting General Data Protection Regulation (GDPR) compliant business practices (Information Commissioner's Office, 2018). To be adopted by end users, the benefits of using AR must be perceived (e.g. utility, time saving, satisfaction) and improve key performance indicators improved for business level adoption (Jetter et al., 2018), for example by expanding company knowledge assets. Working toward "privacy by design" (Chatzipoulidis et al., 2019) and a user centred design approach is intended to improve end user buy in, control and clarify benefit of use (BSI, 2010).

The complex, disjointed nature of AR development remains a significant barrier to wide spread use of AR in industrial scenarios (Masood and Egger, 2020). Current methods for content authoring require a range of expertise including 3D modelling, programming, image processing, tracking and rendering expertise (Bhattacharya and Winer, 2019). Automated content creation techniques attempt to address these challenges, but are inflexible and not suited to changeable or unknown processes (del Amoa et al., 2018). Many AR development techniques rely on adaptation of existing manuals, Computer Aided Design (CAD) models or digital manuals (Haringer and Regenbrecht, 2002; Engelke et al., 2013; del Amoa et al., 2018; Palmarini et al., 2018). In cases where 3D models or PDF manuals are missing or incomplete content creation remains a significant challenge (for example end of life electronics, or legacy systems) (Mohr et al., 2015; Gattullo et al., 2019). Although libraries of symbols and models are being developed, these require continual update alongside the use of fiducial markers for registration of content and complex assignment techniques (e.g. (Scurati et al., 2018; Bhattacharya and Winer, 2019). Fiducial markers may require infrastructure changes (i.e. placement and ongoing visibility of markers), time consuming mapping procedures and ongoing update/management (Palmarini et al., 2018). Natural feature detection avoids the need for fiducial markers but requires accurate 3D models of target items and rendering (Ferraguti et al., 2019) as well as visibility of all relevant parts. Image capture and depth sensors (e.g. Kinect (Gimeno et al., 2013)) may support the development of 3D models without the need for existing CAD, but require invasive capture methods, interruption to workflow and may be unsuitable for industrial environments, furthermore these methods do not capture small or occluded parts (Bhattacharya and Winer, 2019).

The study reported in this paper addresses the need for AR content creation methods to support non-AR experts without the need for content libraries, 3D models, programming expertise or infrastructure change and that are flexible to changing processes and editing. The proposed method was developed to minimise interruption to workflow and transition from traditional interface use to AR interface use. The novelty of the proposed method is primarily the capture of expert tacit and explicit knowledge through the utilisation of eye-tracking combined with information mapping in a template-based service to format and deploy instruction to an AR device. The implementation was evaluated in a use case within an

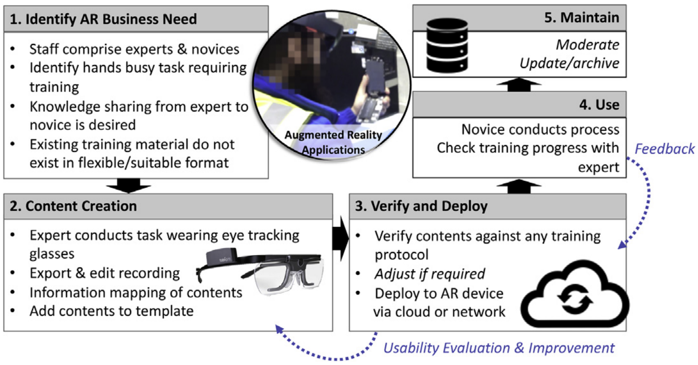


Fig. 3. Multi-modal model framework to support (i) training content creation and dissemination (steps 1,2,3 and 5) and (ii) task completion (step 4).

SE in the European Union moving toward Industry 4.0 readiness. The structure of the paper is as follows; the ARTA methodology is presented in Section 2 and implementation in Section 3. The Augmented Repair Training Application (ARTA) template was utilised in a case study reported in Section 4 with the results in Section 5. Discussion and lessons learnt are presented in Section 6 with conclusion, limitations and further work in Section 7.

2. Methodology

A multi-modal model framework is proposed to support (i) training content creation i.e. the trainer/task expert and (ii) task completion i.e. the trainee/task novice. The proposed framework comprises 5 steps as shown in Fig. 3. Step 1 requires identification of a business need characterised by a desire for flexible knowledge sharing between expert and novice workers to support a hands busy task (Gattullo et al., 2019). Step 2 requires the trainer to complete the task whilst wearing eye tracking and collate the output into training steps. The training steps are added to the template within the Unity 3D development environment (Unity Technologies, 2017). Step 3 enables iterative refinement through usability testing and feedback is obtained throughout use (Step 4). Enterprise improve and retain access to their knowledge assets through maintenance, moderation and archival of data (Step 5) and end users are empowered through knowledge share (Steps 1–4).

2.1. Capturing task steps using eye tracking

The visual and audio contents used to populate the template i.e. the training material, are created using eye tracking whilst the task expert completes the training task. This approach enables content creation without the need for existing resources e.g. PDF manual or CAD. Eye tracking glasses combines the video recording from a front facing camera and audio from inbuilt microphone with a *gaze fixation marker* such as a circle or reticle to indicate where the user was looking during their task (Fig. 4). The eye mind hypothesis suggests that the direction of visual attention, particularly during a visually informed task, is indicative of cognitive attention (Holmqvist et al., 2011). Through the use of eye tracking, a task expert can share both explicit (i.e. task steps) and tacit knowledge (i.e. expert focus) (e.g.(Roads et al., 2016)). The recorded video and audio are exported to free video editing software (iMovie (Apple Inc. 2019)) for information mapping (discussed in Section 2.2).

2.2. Layout and information mapping

The Augmented Repair Training Application (ARTA) template was designed to display contents according to established guidelines (Shneiderman, 2007; BSI, 2010). An *overview* of the steps and current progress was shown using a numbered menu bar (Fig. 5 (b)). Users may select or *zoom* to the selected step and to track their progress by the number (Shneiderman, 2007). User *control and freedom* are provided via self-paced interaction with the instructions (Nielsen and Molich, 1990). The use of metaphors from traditional interfaces are used to help novice AR users adjust to the experience (for example the use of “home”, back and forward controls) (Bowman et al., 2005). To improve legibility, text was displayed in white font with blue accents (Di Donato et al., 2015; Gattullo et al., 2015, 2019).

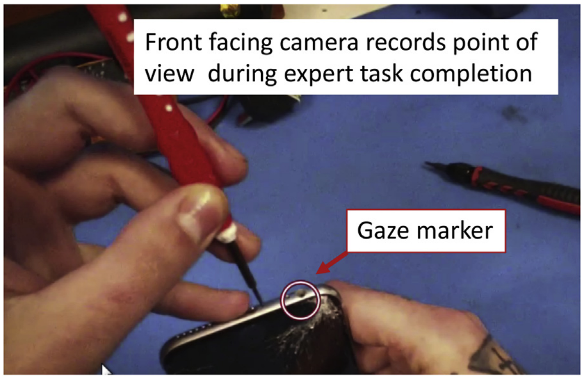


Fig. 4. Eye tracking recording showing point of view of the expert completing task steps (explicit knowledge) and the focus of their visual attention via the gaze marker (tacit knowledge).

Information mapping was used to structure content and improve comprehensibility, in accordance with recommendations for AR instructional manuals (Gattullo et al., 2019). Information mapping consists of: *chunking* (related content i.e. training steps), *retaining relevant information* (simple description (Fig. 5(f)), labelling images (step title (Fig. 5(c)), *checking for consistency* (template formatting (Fig. 5)), *integration of graphics* (Fig. 5(d)) and providing details in a *hierarchical format* (Fig. 5(b)) (Gattullo et al., 2019).

2.3. Verification of learning

Verification of action and learning progress may be required and can be conducted via a learning quiz (Werrlich et al., 2018) rather than blind step following (Werrlich et al., 2017) or digital tools (Danielsson et al., 2018), however these require specific outcomes of task and all variants to be known and quantifiable. Alternatively, experts may be utilised for the verification of successful training and for quality checking of work to increase autonomy and for simplicity (Funk et al., 2015). Expert verification was selected for verification of learning outcome to retain end user autonomy and for simplicity of implementation.

3. Implementation

3.1. Hardware selection

An important practical consideration was the suitability of the AR device for shop floor use in the case study. This resulted in a decision to use the Microsoft HoloLens (Microsoft, 2018a) (from here referred to as the *AR device*) as a higher-quality, cost-effective platform that was considered by the industrial partner to be sufficiently robust for their environment. It is noted that for harsh industrial environments (e.g. extreme temperature, humidity, vibration or dust) the *AR device* may need to comply with standards for example the ruggedisation standard MIL SPEC (U.S. Government, 2008).

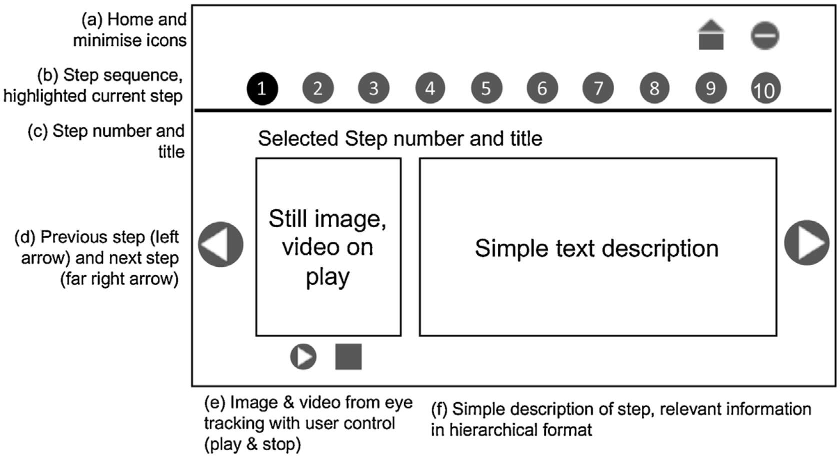


Fig. 5. Layout for the deployed content – black text used in layout format for legibility however in AR environment white with blue is recommended for legibility (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Tobii Pro 2 eye tracking glasses were selected for eye tracking recording due to their ergonomic design (Tobii, 2018).

3.2. Deployment to AR device

The ARTA template was implemented by the EIIS research team using the open source development environment Unity 3D (Unity Technologies, 2017) (Fig. 6(b)) for deployment to the AR device. The trainer adds image and video files exported from the eye tracking software to the Unity folder structure (Fig. 6(d)). The number of steps for the task are adjusted manually in the editable regions within the template (Fig. 6(e)) and each step populated with task step instruction, title, image and video. Note: The option to add audio was not required for the case study but can be added to the clip. The ARTA template design formats the deployed layout and the HoloLens Mixed Reality Tool Kit (Microsoft, 2018b) scripts enables the interactions.

4. Case study

The proposed ARTA method was deployed in a real-world industrial setting to support knowledge share between expert and novice workers for a phone repair task. The method was assessed against two main criteria, (i) *Supporting the trainer*: whether the template and eye tracking approach aided task expert but non-AR expert in the creation of AR-training content and (ii) *Supporting the trainee*: whether the resulting training instructions supported trainee in completion of the repair task.

4.1. The industrial collaborator

The SE involved in the case study operates within the recycling industry and is regulated by the European Union's Waste Electrical and Electronic Equipment Directive (EU WEEE Directive 2002/96/EC). The business focus is on the reception and processing (including repair and refurbishment) of waste electronic and electrical items such as laptops, desktops and mobile devices from financial companies and other organisations. The business recently adopted a novel cyber-physical tracking system to demonstrate and ensure operational compliance to an accredited UK standard (PAS 141: British Standards Institute, 2011) to ensure that data holding assets are securely recorded throughout secure processing (for further details of the system readers are referred to (Sharpe et al., 2017).

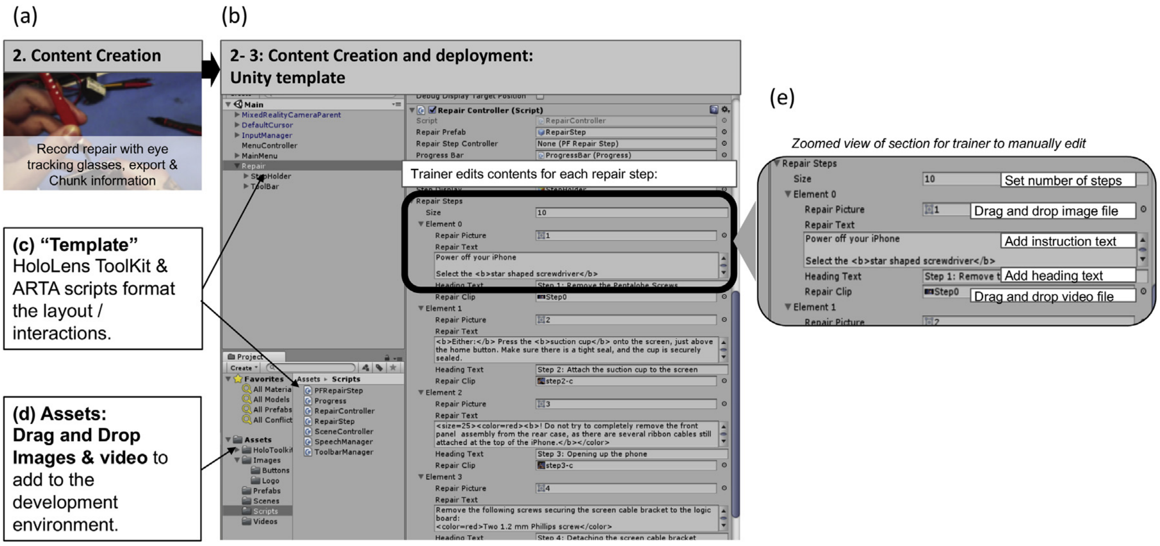
The managing director, sales manager, operations manager and shop floor staff (i.e. supervisors and junior technicians) contributed as key stakeholders. A series of meetings, interviews and observations were conducted to identify requirements and iteratively refine the deployed training tool. The managing director wished to explore the use of AR for knowledge share and as a promotional tool at industrial trade fairs. The replacement of mobile phone screens was selected for the trial as one of the most profitable activities conducted on site. Requirements of the training tool are summarised as follows; (i) reduced time and cost for flexible knowledge share between expert and novice staff, (ii) minimal impact on expert technician's workflow, (iii) must not require 3D models (typically not available nor easily accessed for end of life products), (iv) not utilise fiducial markers (due to the busy workspaces), (v) ideally not use voice command (due to the noisy environment and potential disruption to proximal colleagues) and (v) enable ongoing refinement of training material with the evolution of new makes/models of phone.

4.2. Supporting the trainer

Expert 1 was a male aged 25–30 who had been trained on a 12-week course whilst working in Apple and had been repairing phones for at least 5 years. Expert 1 provided face to face training for expert 2, a female 19–24 who had previously received training at a competitor firm. Both experts conducted between 10 and 50 screen replacement per day, 5 days per week for over 1 year in their current roles. The two expert technicians processed 10 mobile phones each whilst wearing the eye tracking glasses (a typical batch size for the screen replacement task) to capture processing data. The technicians and researchers worked in collaboration to condense and information map the recordings resulting in 10 training steps, videos and image stills. The instructions were iteratively refined (comprising 3 rounds of feedback) with stakeholders in the SE. The ARTA template was populated using the resulting text and exported image and videos from the eye tracking as shown in Fig. 7. The final version was deployed to the HoloLens for usability testing with non-SE employees and subsequently used for company promotion and training support.

4.3. Supporting the trainee

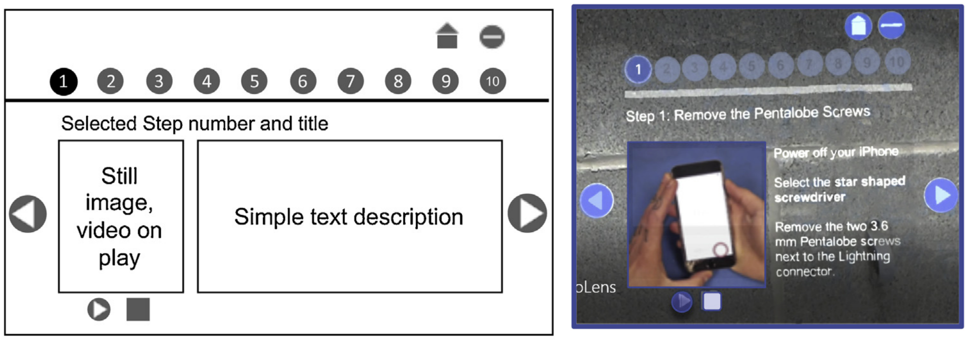
Due to the small size of the SE collaborator the shop floor staff were involved with the development and iterative refinement of the AR support tool so the template. The final version of the AR instructions were evaluated with five participants from the researcher's institution (a sample of 5 is anticipated to find approximately 80 % of usability issues (Nielsen and Mack, 1994)) each



Repair Steps
Size 10
Element 0
Repair Picture 1
Repair Text
Power off your iPhone

Select the star shaped screwdriver
Heading Text Step 1: Remove t
Repair Clip Step0
Element 1
Repair Picture 2

Fig. 6. Overview of the Unity development environment and ARTA template; (a) task recording and information mapping are completed, (b) the unity development environment, (c) the ARTA and MixedReality Toolkit template, (d) trainer adds video and image files, (e) trainer edits number of steps, adds image and text for each step.



Template format

Populated template using SE contents

Fig. 7. Template (left) with deployed template using SE training contents (right).

having no prior experience with the ARTA project. The AR tool was evaluated against the following criteria (i) *task support:* i.e. successful screen replacement without damage or lost parts), (ii) *task workload*: measured using the NASA Task Load Index (NASA TLX) (Hart and Staveland, 1988) and (iii) *usability:* measured using the standard System Usability Scale (SUS) (Brooke, 1996). Additionally, because a person's natural spatial ability (SA) may affect interpretation of instructions into 3D space (Campos, 2012), a Cube Comparison Test (Ekstrom et al., 1976) was administered. Commentary was obtained in addition to the formal usability feedback.

5. Results

5.1. Supporting the trainer

The use of the ARTA method to create AR content was considered to be partially successful. Content was created to support training however; real world use was more complex than anticipated. Participants reported this was due to the unfamiliar Unity 3D environment, eye tracking software and novelty of the device. As a result of end user difficulties encountered during use of the ARTA template, researchers were required to assist the technicians throughout the editing and deployment process and to recover from unexpected errors (e.g. deletion of scripts, moving files). Subjective feedback was obtained from key stakeholders indicating that the resulting training tool was considered a success. The senior management and sales team were happy with the support tool and excitement for further use and they received positive feedback when they demonstrated the AR training tool at a trade show and to their existing customers. The shop floor staff were excited by the novel interface and believed they were being invested in by a company which was keeping up to date with emerging trends. However, a few staff involved did not feel comfortable using the AR device, voice commands or air tap gestures.

5.2. Supporting the trainee

Two females (age 29 and 36) and three male participants (age 31, 41 and 43) completed the usability study. None of the participant had experience of mobile phone repair, one of the participants had replaced a laptop battery and one had assembled a desktop PC. Two participants (1 male, 1 female) had previously used AR. An Apple iPhone 4 mobile phone and repair kit was loaned to the research team by the industrial partner for the purpose of the usability study. Participants reported no physical nor uncorrected visual impairments that would affect precision manual work. Three participants were university graduates, two were non-university graduates (1 male, 1 female). Descriptive statistics are presented for completeness in Table 1. *Task support* was successful and all participants completed the screen replacement successfully, two within 20 min

Table 1
Results of the usability testing conducted with 5 participants.

Participant	Time (minutes)	Spatial Ability (SA)	TLX rating	SUS rating
1	29.88	24	15.6	47.5
2	15.2	14	11.47	95
3	25.49	28	14.67	62.5
4	35.26	32	10.87	47.5
5	16.52	21	12.2	87.5
Mean	24.47	23.8	12.96	68
Std. Error (SEM)	3.85	3.07	0.92	9.95
Max.	35.26	32	15.6	95
Min.	15.2	14	10.87	47.5

(a time scale indicated by the expert as expected for a trainee). *Task workload* associated with using the interface was low (TLX rating 12.96 (±0.92 SEM)). The mean *usability* (SUS rating of 68 (±9.95 SEM, min. 47.5 max 95)) was close to but below the recommended rating of 70 indicating a need for additional refinement (Bangor et al., 2009). Two participants awarded the system a score of 47.5 indicating that for those users the system was not usable. Reviewing the results of the participants who rated the system 47.5, they were also the slowest to complete the task (35.26 and 29.88 min). It is noted that the highest spatial ability participant took the longest to complete the repair (SA = 32, time = 35.26), whereas the lowest spatial ability participant completed the fastest repair (SA = 14, time = 15.20).

Participants reported difficulty regarding appropriate forces to be applied to small parts and would like feedback to be provided in the AR environment, additionally they requested audio and the ability to “pin” instructions in a position of their choosing rather than having the heads-up display. The AR device was not suited to long wear times due to the battery life and ergonomic concerns (fit and weight) as well as fatigue from gesture interaction and hygiene concerns regarding shared device use were reported by all participants.

6. Discussion

A summary of the observations and results of the case study are presented in Table 2 showing issues and recommendations grouped according to *known* (e.g. (Dey et al., 2016; Bowman et al., 2017)) and *emerging items*. The main *known* concern regarded ergonomic discomfort caused by the AR device (current state of the art at time of deployment was Microsoft HoloLens). Usability participants requested feedback on their actions regarding forces applied and whether they were completing the task correctly. The proposed method relied on verification of success or failure of the task by the expert, this would be unsuitable for remote work or particularly delicate or high-risk task (i.e. cost or safety). Previously mentioned verification methods (e.g. quiz, remote dial in of expert) could be utilised or digital tools used for measuring torque or visual inspection of finished items (e.g. (Ferraguti et al., 2019). Unfortunately, the current state of the art techniques requires 3D modelling, reliable tracking/rendering of 3D contents and visibility of all parts and considered unsuitable for the repair task and requirements specified.

Emerging issues included the use of the ARTA template by the trainer/expert. Although established guidelines were used and the editable regions of the template highlighted to the expert, the potential to “break” the Unity 3D template through deletion of code or accidental moving of files combined with the unfamiliar Unity environment made populating the template difficult and somewhat stressful for the experts. The technicians utilising the template required assistance from the researchers to edit, populate and recover from errors within the Unity 3D environment. The privacy afforded to individual users was appreciated by the shop floor staff (i.e. no one can see your screen) and may be useful within environments where staff have access to protected information, are employed on variant levels of security access or if customer tours are common. However, this has the potential to encourage non-work activities to be conducted on the AR device if access was permitted.

The shop floor staff (industrial) and usability participants (researchers) had different expectations and needs regarding the interface including level of expected editability and adjustment. The usability participants requested additional sensory encoding (audio), interaction methods (voice control, image zoom and the ability to attach the interface to a real-world location) whereas the shop floor staff required a simple visual interface with minimal interaction. Although the template had the capability to support voice control and pinning of the interface to surfaces (a feature of the Mixed Reality Toolkit), provide audio (recorded and provided with the video files), these were not implemented in the

Table 2
Summary of lessons learnt and guide for "Do" and "Don't" associated with AR implementation.

	Recommendation	Issues/Potential Problems
Known	• Engage management and target users • Observe task and assess the suitability of AR • Consider hygiene, charging period and comfort of wearables. Minimise use time. • Communicate issues and provide feedback (good and bad) to management, development team and end users. • Ensure informed consent prior to commencement of any data recordings. • Keep participants informed of project progress and the reasons for recording their data. • Listen to suggestions and requirements. • Allow adaptation for advanced AR users	• Ongoing management, maintenance and moderation of AR content needs to be integrated within wider business processes • The programme should be built with the goal of self-sufficiency in mind to empower shop floor workers in order to support their own in-house training. • Reliance on expert verification of completion of work task requires availability of expert to act as quality controller.
Emergent	• ARSG may provide users with increased privacy aiding compliance with GDPR, protect customer sensitive data and enable varying levels of employee access to company assets. • An intermediary interface between the user and the AR development environment could provice a “one stop” zone for editing content and formatting layout in a “what you see is what you get” environment. The interface provides a safe editing space between the technical development environment (e.g. Unity 3D), scripts, data storage and the end user.	• Colleagues with a high level of informal or social interaction interfere with neighbour’s interface if voice and gesture controls are active, user specific control recognition may be required. • AR development environment requires support for all stakeholders • If end users have access scripts and IDE they may feel overwhelm, accidently delete or move content

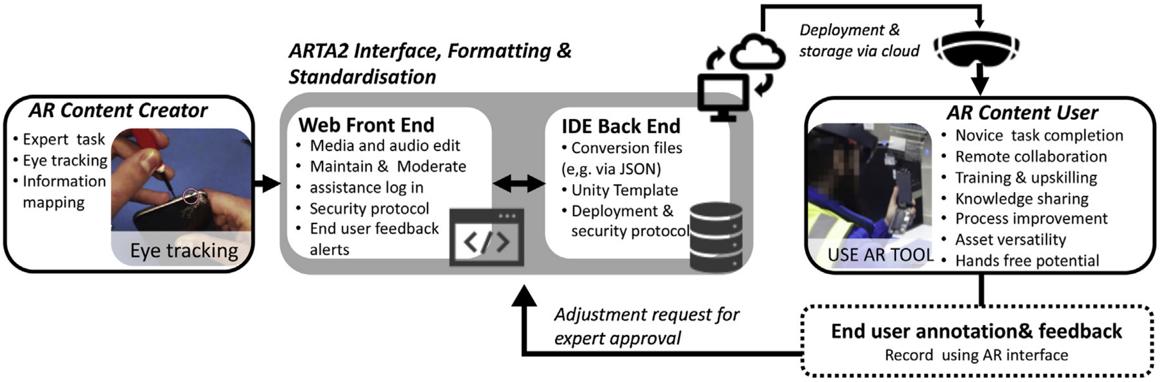


Fig. 8. Intermediary content editor for end user with back end conversion for deployment via cloud.

case study at the request of the SE team for the case study. During the initial requirements capture and iterative refinement of the interface design the use of voice command and audio were determined to be unsuitable for the shop floor. The case study environment included a sociable staff and a collaborative workspace, the high level of camaraderie was beneficial to providing support between staff, however this also led to AR interface use issues. Firstly, colleagues would to attempt to take control their neighbours' interface by speaking or gesturing at them. Additionally, the onboard language processer did not work with users with strong regional accents nor non-native English speakers failing to recognise the command "next", "previous", "minimise" or "hide" which caused visible embarrassment and frustration.

Based on the feedback and lessons learnt through the process of designing an AR content creation support tool, the authors recommend the development of an "intermediary interface" to provide restricted editing in a form-based layout for simplified interaction with an underlying "back end" service for conversion of input to the necessary AR code, illustrated in Fig. 8. The intermediary interface would reduce the difficulties encountered within the study and is proposed for further work comprising form style input, inbuilt tools to enable video, audio and text editing from eye tracking data and a additional help functions and documentation in the form of tool tips adjacent to each section for completion. The Integrated Development Environment will be removed to the back end to securely store and run the scripts for formatting and deployment to the selected AR device with a "bootstrap" style adjustment to suit form factor (e.g. grid-based formatting). Additional security could be implemented within this separated feature to ensure that content is moderated prior to deployment, protected from unintended access and that the underlying formatting is not corrupted through use.

7. Conclusions, limitations and further work

The research helped an SE explore the value of using AR whilst causing minimal disruption to shop floor workflow and limited financial investment, however the need for data protection, maintenance and storage were not directly addressed. The ARTA template was designed to be generically applicable and although successfully deployed within an SE, deployment and usability evaluation were for a prototype application used in the short term with a small pool of participants. A longer-term feedback procedure would be required for refinement as the user experience evolves over time and to develop more dynamic knowledge sharing. Further work such as longitudinal studies are required to determine the level of growth supported by sharing knowledge through AR and the long-term effects of using AR devices.

A limitation of the study was that the technique was developed to retain a high level of autonomy within the staff. The technique relied on the expert determining whether a colleague was expert or novice and did not consider the assessment of skills in the user prior to nor after training, nor tailor content to the users' requirements. For a remote expert, or automated process there is a need for appropriate assessment techniques and monitoring of the workers performance. However, due to the difficulty of identifying skill level in complex manual tasks and the complexity of providing individualised instruction to suit user, task and skill level this remains an active area of research. Additionally, the use of any automated components for assessment may cause mistrust and reduce workers sense of autonomy, an essential component of human work (Yost et al., 2019). Potential negative effects of removing personal freedom or autonomy through workplace monitoring have been associated with increased work arounds and undesirable behaviour used to regain perceived control (Ehrenbrink and Möller, 2018; Yost et al., 2019). Furthermore, any support tool resulting in the storage of data relating to the working environment, products or processes may increase security risks for or leakage of company IP. The tasks recorded during the present study were not considered to be vital intellectual property, however an alternative industry may require additional protection and a more rigorous moderation of content with strict sharing protocols.

Although not investigated in the research outlined in this paper, the complexities of the relationships emerging between user, task, environment and the characteristics of the interface (comprising visual encoding and platform) may require an *ontological approach to address the above interoperability concerns*. Such an approach requires contributions from a range of disciplines (e.g. system designers, engineers, computer scientists, analysts, human factors experts, industrialists) and a standardised approach to user testing and trials (e.g. considering device, visual encoding, user and environment).

The method and evaluation presented in this paper was focused on the design and evaluation of a novel content creation methodology to evaluate the suitability of AR for the support of a training task scenario within the electrical and electronics equipment end of life domain. In addition, the research explored some of the consequential aspects of embedding AR technologies in the pursuit of organisational aspirations and strategies for sustainable growth that, for example, will be necessary to be "fit for purpose" when adopting the I4.0 paradigm. The prototype interface demonstrated an approach to transition enterprise from traditional interfaces (e.g. desktop computer) to AR technologies through the use of a template-based formatting tool and novel content creation technique (eye tracking recording and information mapping). The development of a further intermediary interface (Fig. 8) is planned as further work and a steppingstone for small and medium enterprise to adopt AR interfaces and determine the efficacy of such systems with minimal investment of time and resource.

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Data statement

In accordance with the funding body, access to anonymised data from the usability study are available via the university repository.

CRediT authorship contribution statement

Katherine van Lopik: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Murray Sinclair:** Writing - review & editing. **Richard Sharpe:** Software. **Paul Conway:** Funding acquisition. **Andrew West:** Resources, Funding acquisition, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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