Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 38 (2015) 14 – 23
www.elsevier.com/locate/procedia

The Fourth International Conference on Through-life Engineering Services

Application of Augmented Reality Techniques in Through-life Engineering Services

G. Dini, M. Dalle Mura*

Department of Civil and Industrial Engineering, University of Pisa, Via Diotisalvi, 2, Pisa 56122, Italy
* Corresponding author. Tel.: +39-050-2218011. *E-mail address:* m.dallemura@ing.unipi.it

Abstract

Augmented Reality (AR) is an innovative human-machine interaction that overlays virtual components on a real world environment with many potential applications in different fields, ranging from training activities to everyday life (entertainment, head-up display in car windscreens, etc.). The capability to provide the user of the needed information about a process or a procedure directly on the work environment, is the key factor for considering AR as an effective tool to be also used in Through-life Engineering Services (TES). Many experimental implementations have been made by industries and academic institutions in this research area: applications in remote maintenance, diagnostics, non-destructive testing, repairing and setup activities represent the most meaningful examples carried out in the last few years. These applications have concerned different working environments such as aerospace, railway, industrial plants, machine tools, military equipment, underground pipes, civil constructions, etc. The keynote paper will provide a comprehensive survey by reviewing some recent applications in these areas, emphasizing potential advantages, limits and drawbacks, as well as open issues which could represent new challenges for the future.

Peer-review under responsibility of the Programme Chair of the Fourth International Conference on Through-life Engineering Services.

Keywords: Augmented Reality, Through-life Engineering

1. Introduction

Augmented Reality (AR) is an innovative technology able to supplement a real-world environment with computer-generated sensory inputs. These virtual components seem to coexist with real ones in the same space, enhancing the user's perception of reality and enriching the provided information content. Thanks to the considerable improvement in the quality and effectiveness of human-machine interaction, the use of this technology is shifting from laboratories and academic institutions around the world to different industrial contexts and consumer markets.

The first researches in this area were carried out in the 60's by Ivan Sutherland at Harvard University [1], but it was during the 90's that AR reached concrete experimental results, applicable on a large scale. Currently, there are many application areas for AR, ranging from the engineering field to various aspects of everyday life.

AR has been defined as a human-machine interaction tool that overlays computer-generated information on the real-world environment [2] and can be described as a set of three key features [3]:

- combination of real and virtual objects in a real environment;
- real-time interaction with the system, able to react to user's inputs;
- geometrical alignment of virtual objects to real ones in the real world.

The strengths of AR can be identified as follows:

- immersive system: information are directly integrated in the real world;
- immediate interpretation of information: the provided messages are easily understandable by the user;
- paperless ability to provide a large amount of knowledge;
- possibility of integrating the system with other computer-aided devices;

Peer-review under responsibility of the Programme Chair of the Fourth International Conference on Through-life Engineering Services.
doi:10.1016/j.procir.2015.07.044

- faster procedures: the operator does not detract the attention from the real environment, while consulting procedural instructions.

These characteristics may vary, depending on the technique used to implement the AR. Thus, the different types of systems currently available to realize this integration between reality and virtuality are classified and analyzed.

The paper has been organized as follows: an overview on the current AR techniques has been provided in section 2; the advantages of combining AR and TES have been presented in section 3; a description of the state-of-the-art literature for AR applications in TES has been provided in section 4; open issues to direct future researches have been presented in section 5, as well as current limitations mainly due to some hardware and software problems, obviously still existing in these very innovative and revolutionary systems.

2. Overview on AR techniques

To combine virtual objects and real images, one of the following methodologies can be used, according to the method of overlaying virtual components on the real world environment:

- Optical combination: virtual images are projected in the visual field of the user, while he directly observes the real scene.
- Video mixing: digital information are acquired by a camera and reworked by a computer. The result is then displayed on a monitor through which the user indirectly observes the real scene.
- Image projection: images are directly projected on the surfaces of physical objects.

The main hardware components required for performing AR applications and their functions are:

- Computer; besides creating virtual contents and managing all the devices, it has to collimate the virtual content and the position of the observer with respect to the scene, according to the information coming from the tracking system.
- Display device; three different categories exist, depending on the position occupied with respect to the user and to the observed object: i) Head-Mounted Display (HMD), worn on the user's head; ii) Hand-Held Display (HHD), like tablet or cell phone; iii) Spatial Displays (SD).
- Tracking system, necessary to obtain and record the user position and orientation in space, in order to properly align the virtual image to the real one.
- Interaction tools, such as touchpads or wireless devices, to be used as additional input devices.

3. AR and Through-life Engineering Services

Through-life Engineering Services (TES) deal with the needs of asset management, condition monitoring and damage tolerance of high-value products and systems, through the entire lifecycle. Some key features of the activities related to TES can be summarized as follows:

- These activities are often subject to standardized procedures to be carried out.
- These activities require extensive information, usually available on bulky manuals.
- These activities usually have to be carried out "in the field".

AR therefore combines extremely well with these characteristics, allowing e.g. an easy access to technical documentation without using paper manuals. TES, however, must closely interact with products and processes. Thus, when using AR it is necessary to interface it with sensors in order to monitor the environment and provide all the necessary information. These sensing devices should interact with the AR systems, transmitting any significant changes in the states of the user surrounding area. For instance, an AR-guided maintenance procedure should determine, through robust and accurate sensing, the current status of the product to be processed, or the location of the real elements where the virtual ones will be superimposed. A robust AR system also requires robust software algorithms for processing the huge amount of data coming from these sensing devices [4].

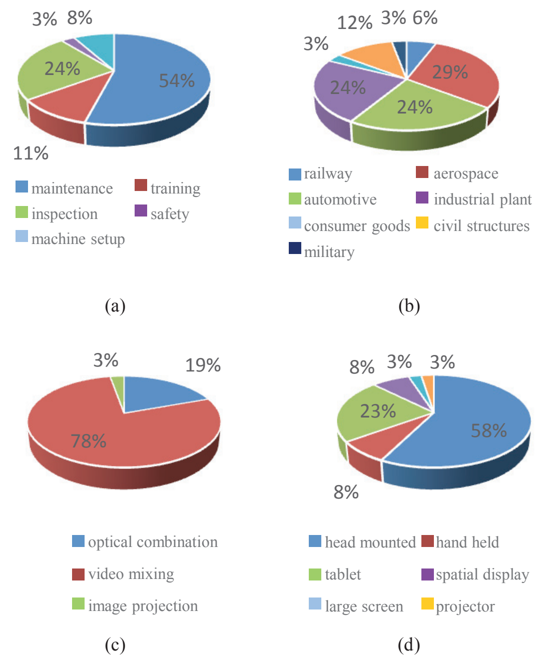


Fig. 1. Distribution of AR applications in TES, with reference to: (a) service; (b) area of application; (c) AR overlaying method; (d) AR display device (results obtained by analyzing 53 contributions).

4. AR applications

All the above-mentioned considerations, in recent years, have led to the development of various AR applications in

Through-life Engineering Services. A distribution overview is given in Fig.1.

An analysis of the previous data clearly shows that most applications can be found in maintenance, repairing and inspection tasks, while the areas with a great number of applications are aerospace, automotive and industrial plants. As far as implementation is concerned, the most used method for overlaying virtual components on the real world is undoubtedly represented by the video mixing technology (for its intrinsic more immersive approach), using HMD for displaying the information to the user, although the use of the tablet is ever more common, especially in the latest applications.

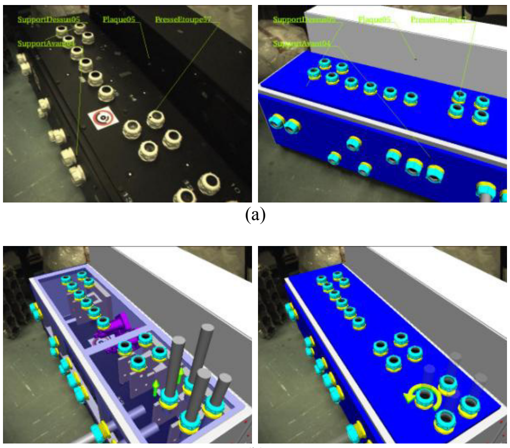
In the following, some meaningful applications have been described and analyzed in order to emphasize the key features of the AR potentials in the typical fields of TES.

4.1. Maintenance and repairing

Maintenance and repairing activities present a great number of AR applications, using various overlay methods and hardware. Undoubtedly, the operations accomplished during these kinds of activity are well supported by the virtual information sequence given by an AR system.

A first example of application concerning train maintenance is described in [5]. The task is to perform an operation on an electrical transformer, where the system uses CAD models of the parts and visual hints for retrieving their names and illustrating to the user the maintenance steps, as illustrated in Fig.2.

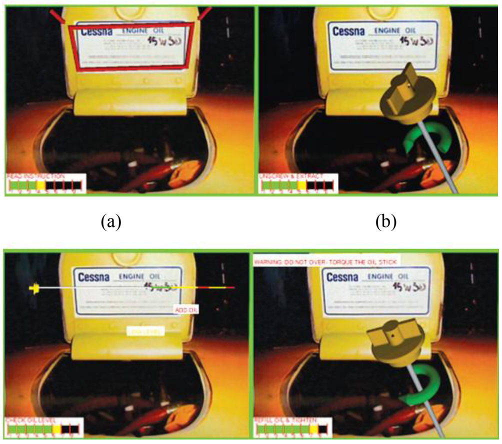
Many contributions have interested the area of aerospace applications. An optical device has been used to recognize markers placed on aircraft components [6]. As illustrated in Fig.3, the user can position a see-through combiner lens in front of either eye and receive virtual text information from the system.



(a) (b)

Fig. 2. Screenshots of a maintenance procedure on an electrical transformer of a train (source: [5]): (a) retrieving name of transformer's parts; (b) animations illustrating a maintenance step.

Fig. 3. A mobile AR system with HMD used in aircraft maintenance activities (source: [6]).



(a) (b) (c) (d)

Fig. 4. Oil check procedure of an aircraft supported by an AR video mixing approach (source: [7]).

The detailed sequence of operations to be performed in a oil-check procedure is visualized by the system proposed in [7] and shown in Fig.4: a red 3D rectangle frames the information to remind the operator to read it, (Fig.4.a); the model of the oil dipstick rotates counterclockwise and moves upward to indicate the operation to be emulated (Fig.4.b); the different oil levels are shown using color-coded information (Fig.4.c); the dipstick rotates clockwise and moves downward to show how to reinsert it (Fig.4.d).

The maintenance activities concerning a Rolls-Royce Dart 510 turboprop engine have been investigated in [8,9]. In particular, an AR prototype for providing assistance during procedural tasks has been developed. Fig.5 shows an example concerning the correct alignment of combustion chamber parts: a red and dynamic arrow indicates the needed motion in direction and magnitude (Fig.5.a); the arrow changes size and color as can and cone begin aligning (Fig.5.b) and, if necessary, specifies shortest rotational direction to alignment (Fig.5.c); the arrow disappears when alignment is achieved (Fig.5.d).

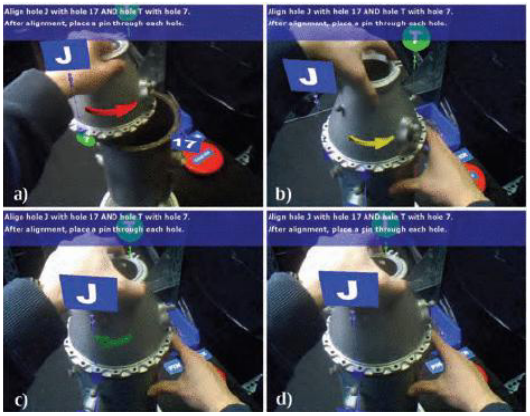


Fig. 5. AR procedure for supporting operator in performing maintenance task on a combustion chamber of a Rolls-Royce Dart 510 engine (source: [9]).

Another research [10] proposes an Intelligent Augmented Reality (IAR) system to help aircraft technicians facing complex procedures for their maintenance tasks and to minimize operation errors and time-related costs by using an intuitive interface. Overall testing of the IAR system has been conducted at Korea Air Lines hangars. An example is shown in Fig.6.

Fig. 6. Operator's view of the IAR system during the maintenance of an aircraft undercarriage (source: [10]).

AR solutions have also been experimented in space applications, such as the optical see-through device used in space station filter change and described in [11].

An example in the automotive sector is given in [12]. In this application, a BMW 7-series engine was used to test the system. The solution for AR-based repair guidance consists of a markerless CAD-based tracking system able to deal with different illumination conditions during the tracking stage and to automatically recover from occasional tracking failures. Two hardware solutions were experimented, based on a wireless mobile setup: a monocular full-color video-see-through HMD and with a monochrome optical-see-through HMD (Fig.7).

An interesting example of self-maintenance is reported in [13]. I-Mechanic is one of the first examples of AR application for smartphones to support people in ordinary maintenance of their car. With this mobile application, based on a computer vision 3D tracking software, the user is able to contextually access the instructions required to accomplish simple maintenance operations, as shown in Fig.8.

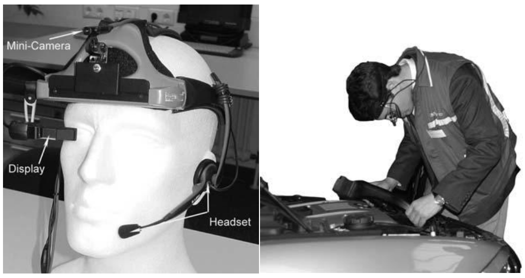


Fig. 7. Optical see-through HMD used in the maintenance procedure of a commercial vehicle (source: [12]).

Fig. 8. AR-based system to support people in ordinary maintenance of their car (source: [13]).

A similar application of car repairing is described in [14], where a new type of 3D tracking technology does not require markers, GPS or point cloud. The system utilizes CAD models to recognize and overlay 3D content onto the real workspace.

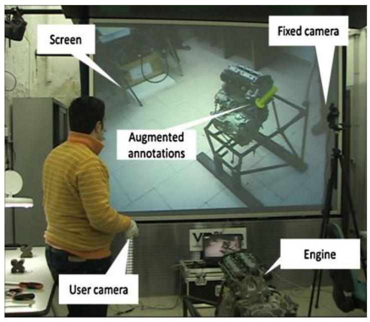


Fig. 9. Interactive AR instructions on a large-screen for the maintenance of a motorbike engine (source: [15]).

Another approach consists of an augmented visualization on a large screen and a combination of multiple fixed and mobile cameras for maintenance tasks based on manual inspections of a motorbike engine [15]. Tool selection, removal of bolts, and part disassembly, are supported by visual labels, 3D virtual models and 3D animations. The screen-based video see-through display is shown in Fig.9.

Industrial vehicles have also been under experiment for an application of an AR support [16]. The engine of a hydraulic excavator has been taken as an example. The maintenance crew's task is to test hydraulic oil from sampling valves for preventative maintenance. The media representation is text and/or 2D-image/video. Remote server module consists of several experts and a central database server. Identification module uses RFID technology to identify equipment.

Maintenance in industrial plants is another application of AR.

An AR voice-controlled device is described in [17] and used in nuclear powerplants. An example of maintenance session is as follows: the user requires to see the next step by saying "Computer, next step"; a computer-generated voice returns the maintenance information "Close valve V2000" while valve V2000 is highlighted in the worker's HMD. In addition, an LCD screen shows the closing procedure, as well as the work order.

Another speech-enabled AR framework (named SEAR) for mobile maintenance is presented in [18]. SEAR consists of a 3D Virtual Reality Markup Language component, speech-recognition and speech synthesis engines to allow a spoken dialogue in a vision-based marker-tracking system with 3D objects. Fig.10 shows the SEAR prototype user interface: in the industrial equipment view pipes and pumps were augmented in red to highlight features.

Fig. 10. SEAR prototype user interface showing an augmented view of industrial pipes and their equipment (source: [18]).

Consumer goods, and PC in particular, represent a diffuse topic of maintenance activities supported by AR. In [19], a system for maintaining PC equipment is depicted. The key hardware feature is a binocular video see-through HMD; the tracking system, which gives the position and orientation of equipment, has been implemented using ARToolKit (freeware library for building AR applications). A similar system is described in [4]. Step-by-step instructions can be displayed to the technician when servicing a computer CPU without sensors or markers, as shown in Fig.11.

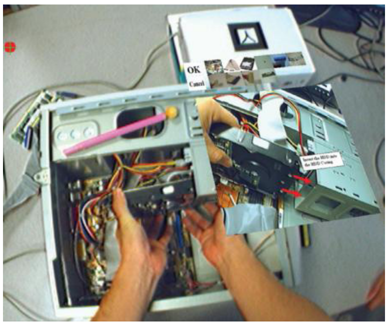


Fig. 11. AR-assisted maintenance of a computer CPU (source: [4]).

In the field of civil engineering, AR systems have been used in maintaining underground infrastructures. An example can be found in [20], where the tracking of these structures is provided by a combination of a GPS device and an inertial unit. Fig.12 shows the 3D model of the underground infrastructure superimposed on a construction site.

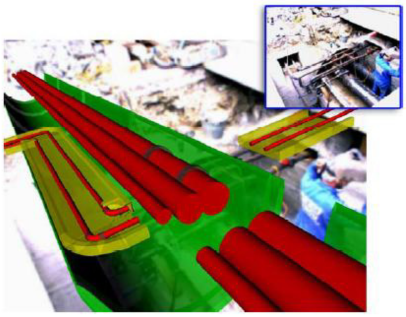


Fig. 12. 3D model of underground infrastructures superimposed on a construction site (source: [20]).

(a) (b)

Fig. 13. (a) A mechanic wearing an HMD performs a maintenance task inside an armored personnel carrier. (b) Operator's view through the HMD (source: [21]).

Repairing of military vehicles and equipments supported by AR has been described in [21]. The prototype supports

United States Marine Corps mechanics operating repair tasks inside the turret of an LAV-25A1 armored personnel carrier. Two different devices have been tested, a head-worn device (Fig.13) and a wrist-worn controller using an Android G1 phone (HHD).

AR techniques have a great potential in remote maintenance applications, capable of providing the mixed image (virtual and real) simultaneously to the worker on the field and, remotely, to the expert assistant.

In this context, the research conducted in [22] describes an AR strategy for aiding the remote collimator exchange in an energy particle accelerator. The research [23] explores whether and how virtual co-location based on AR can be used to remotely support maintenance during space missions, wearing an HMD (Fig.14).

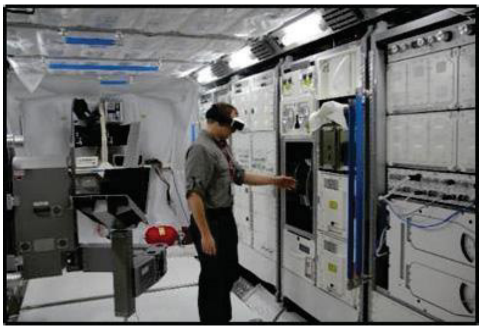


Fig.14. Trainee wearing a HMD inside the space laboratory of the ISS (International Space Station) during a remote maintenance session (source: [23]).

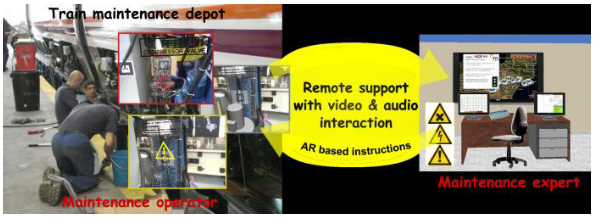


Fig. 15. Remote maintenance in a train depot using AR-based instructions (source: [24]).

AR remote maintenance sessions have also been experimented in the railway sector [24]. As illustrated in Fig.15, the remote support of the expert is obtained by means of video and audio interaction, using AR-based instructions to help the on-site worker to perform the operations.

4.2. Diagnostics, fault detection, inspection and testing

The AR technology has been recently introduced to Non-Destructive Testing (NDT). A meaningful example of application is represented by the inspection and mapping of defects with a 3D image [25]. The position of defects is indicated on the pipe and clearer insight into the scale and nature of defects are given. The operator can detect, locate and mark the defect using only a tablet (HHD device) and a marker (Fig.16).

Another mobile solution for NDT and quality control services can be found in [26], where the system MiRA (Mixed Reality Application) superimposes the digital mock up to the reality with a tactile tablet as hardware.

In [27] a method for the support of diagnostic processes is presented. In the developed solution, diagnostic processes are executed via the visual presentation of the following: i) location of the device components, ii) diagnostic tasks, iii) descriptive hints, iv) measurement values, v) location of the measurement points and vi) 3D models of the components (Fig.17).

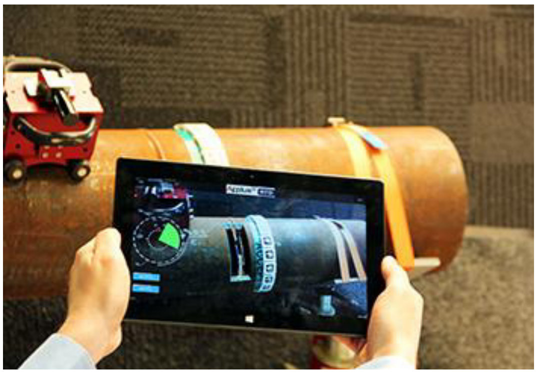


Fig. 16. AR applied to non-destructive testing on pipelines through HHD (source: [25]).

Fig. 17. Example of a screenshot of an AR system used to support diagnostic processes in an electrical panel (source: [27]).

Some car manufacturers are developing AR-based diagnostics systems to be used in workshops. The solution depicted in [28] fuses object recognition, tracking and task oriented user interfaces to deliver unparalleled workshop efficiency. Parts and components that need to be analyzed are marked and presented in a display that allows a step-by-step diagnostics. In [29], the data from the sensors, such as tire air pressure, are analyzed and presented in visual form on a HHD. The proposed solution overlays virtual information in the exact position of the vehicle corresponding part (Fig.18).

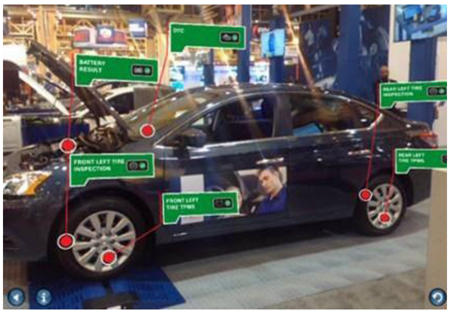


Fig. 18. AR diagnostic system used in car workshops. The worker points his tablet at the vehicle and receives an immediate diagnosis of the major systems in real-time (source: [29]).

Inspection is also an important issue in civil structures. The research [30] proposes an AR-assisted non-contact method for estimating Interstory Drift Ratio (IDR: an important indicator of structural performance in buildings), without requiring any pre-installed physical infrastructure. The corner locations in a damaged building are detected by an image analysis approach, by intersecting horizontal baselines and vertical edges. The horizontal baselines are superimposed on the real structure using an AR algorithm (Fig.19).

Fig.19. HMD device used for the structural inspection of a building (source: [30]).

Fig. 20. Inspection of the instrument panel of an aircraft by an HMD (source: [31]).

It is well known that inspection procedures are very important in the aerospace area. In this context, a prototype of HMD [31] was implemented to provide a daily inspection task for aviation industry and validated on 3 different airplanes. Fig.20 shows the experiments carried out in performing an inspection task of the instrument panel to be performed before flight.

4.3. Training

A typical application of AR devices, not only in through-life engineering services, is training of personnel.

A first example is given in Fig.21 [32]. This application represents an AR-based training process to perform maintenance on the body of the RV-10 aircraft. The system is able to correctly identify the real objects and superimpose the virtual elements, congruently with the estimated real world reference frame.

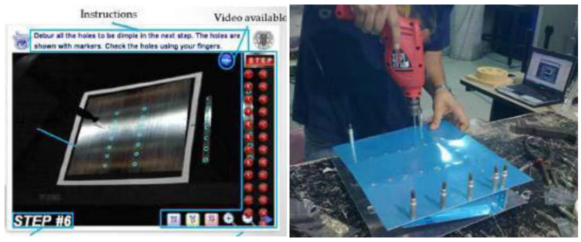


Fig. 21. Use of AR for training of personnel in repairing operations of fuselage panels of RV-10 aircraft (source: [32]).

In the system described in [33], the training of personnel in interventions in different scenarios is obtained using an HMD with a small camera, with which personnel stands in front of a blue screen. The camera captures an image through which the system recognizes an object position and orientation, by image processing without any special marks or sensors. After that, the system uses Chroma-Key image composition for combining the real objects and virtual scenes (Fig.22).

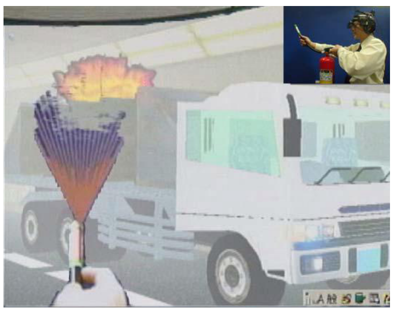


Fig. 22. Example of a displayed image on an HMD during a fire-fighting training exercise (source: [33]).

4.4. Safety

AR systems can also be used for enhancing safety level in performing different tasks. The system described in [34], for instance, proposes techniques of enhancing the visual perception of construction equipment personnel to improve work safety in urban projects. The research objective is being pursued by an AR device and a Global Positioning System to integrate real time views of construction operations with CAD models of the underground utility lines, that are overlaid on live video streams of the jobsite.

4.5. Machine setup

Through-life engineering services can also be extended to manufacturing systems and, therefore, are not only limited to maintenance and inspection activities. Machine setup, production changes and process restart represent important steps during the life of manufacturing systems that could require AR-based support systems.

In [35], AR has been used to integrate process data with the work environment of an industrial CNC machine. This system consists of an optical see-through and spatial AR system (SD), which is used to provide real-time 3D visual feedback, no requiring equipment to wear for the user. Onto the safety glass a transparent holographic optical element is superimposed to the tool and the workpiece, providing bright imagery clear visibility, also of occluded tools (Fig.23). The realized system allows a real-time data visualization from the process in the workspace, where the graphics are geometrically registered to provide an intuitive representation of the process.

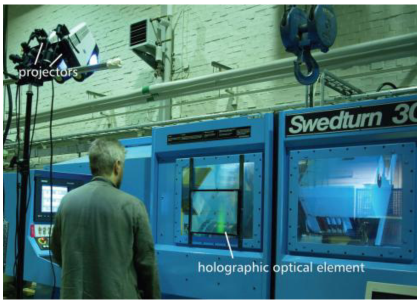


Fig. 23. AR application in CNC machine setup: a worker views the machine operation through a holographic optical element, illuminated with stereoscopic images from the projectors driven by a PC (source: [35]).

Another example in this field is represented by the EU-funded project FLEXA (Advanced Flexible Automation Cell) [36,37,38]. The project has concerned the development of two demonstrator cells: one was for grinding and measuring operations, and the other for welding and non-destructive testing of aircraft engine parts. Different AR systems have been used for performing both machine setup operation and process restart procedures after plant failures. A first example is represented by a video mixing approach, used as a support during the setup of a CNC grinding machine: the worker can see the virtual instructions on the real scene by means of a tablet (HHD), as shown in Fig.24.

Fig. 24. A tablet used by the worker during the setup of a CNC grinding machine (source: [36,37,38]).

The other AR-based system has been developed as a support tool in restarting procedures of the manufacturing cell. In this case, an HMD is used by the worker during the different steps of the procedure (fig.25).

(a) (b)

Fig. 25. AR system used in process restart of a manufacturing cell: (a) an operator executes the AR-guided procedure; (b) a screenshot concerning a single procedural step (source: [36,37,38]).

5. Open issues for further research and limitations

The capability of AR to provide the user of the needed information about a process directly on the work environment has meant that in TES many experimental AR implementations have been made. Despite this progress in recent years, AR applications are still in an exploratory stage, with some limitations to be solved. As relevant technologies, tracking and registration algorithms further improve, it is expected that AR will more effectively assist TES in the near future.

AR would offer more benefits in the future through the interaction with sensorial devices for a real-time visualization on the current status of the system and through the integration with simulation software for a real-time estimation on the current simulate status of the system. Thus, the full potential of an AR system for TES applications would be achieved. Future researches should be focused to these very promising solutions, with the development of integrated systems which begin to appear in other industrial fields [39].

Currently, AR faces technical challenges, such as the usability and portability of the hardware. Many mentioned mobile systems are cumbersome, heavy and the user could suffer of eye strain after long periods, whereas other equipments are not yet completely wireless. Moreover, optical and video see-through displays are usually unsuited for outdoor use due to their dependency on lighting conditions.

Various of the many HMDs developed show a small field of view, becoming a real occlusion to work execution. Moreover, this limited peripheral visibility could give safety problem to the user. Visual quality of overlaid images also need enhancement.

As far as the calibration of AR devices is concerned, weaknesses of some applications cause system delays thus complicating the tracking process. Future work should involve going towards markerless tracking systems. In some prototypes, the speech interaction of the system, which needs the vicinity of the user for speech-enabled equipment, could be a problem.

Another great limitation of AR is represented by long delays to face in the preparation, programming and setting up of these systems. This fact should stimulate toward the development of methods that facilitate these steps by creating, for example, self-learning systems.

6. Conclusions

The capability to provide the user of the needed information about a process or a procedure directly on the real environment, represents the key factor for considering AR an effective tool in TES. This paper demonstrates that many experimental implementations have been made by industries and academic institutions: applications in maintenance, repairing, diagnostics, testing, training, safety and setup activities have been successfully experimented, although some open issues still exist concerning both hardware and software aspects.

At the end, it is very important to emphasize that a continuous evolution of hardware and software systems can be noticed in the market. For example, the recent developed Google Glass and Microsoft Hololens, still in an experimental stage, introduce new capabilities to the future systems in terms of portability and comfort of AR apparatus. Furthermore, the latest markerless AR softwares, increasingly robust and sophisticated, should permit an easier programming and setup stage. New solutions in such a sector are in constant expansion and will surely bring results still unpredictable that will overcome the currently existing limits, previously outlined.

References

[1] Sutherland I. A head-mounted three dimensional display. Proceeding AFIPS '68 (Fall, part I); 1968. p.757-764.

[2] Reinhart G, Patron C. Integrating Augmented Reality in the Assembly Domain - Fundamentals, Benefits and Applications. CIRP Annals - Manufacturing Technology; 2003. p.5-8.

[3] Azuma RT. A survey of augmented reality. Presence: Teleoperators and Virtual Environments; 1997. p. 355-385.

[4] Yuan M L, Ong SK, Nee AYC. Augmented reality for assembly guidance using a virtual interactive tool. International Journal of Production Research; 2006.

[5] Didier JY, Roussel D, Mallem M, Otmane S, Naudet S, Pham Q, Bourgeois S, Mégard C, Leroux C, Hocquard A. AMRA: Augmented Reality Assistance for Train Maintenance Tasks. 4th ACM/IEEE Int. Symp on Mixed and Augmented Reality; 2005.

[6] Haritos T, Macchiarella ND. A mobile application of augmented reality for aerospace maintenance training. 24th Digital Avionics Systems Conference; 2005.

[7] De Crescenzio F, Fantini M, Persiani F, Di Stefano L, Azzari P, Salti S. Augmented Reality for Aircraft Maintenance Training and Operations Support. Computer Graphics and Applications, IEEE, Volume 31, Issue 1; 2011.

[8] Henderson SJ, Feiner SK. Augmented Reality for Maintenance and Repair (ARMAR). 8th IEEE International Symposium on Mixed and Augmented Reality, Science and Technology. ISMAR; 2009.

[9] Henderson SJ, Feiner SK. Augmented Reality in the Psychomotor Phase of a Procedural Task. IEEE International Symposium on Mixed and Augmented Reality; 2011.

[10] Jo GS, Oh KJ, Ha I, Lee KS, Hong MD, Neumann U, You S. A Unified Framework for Augmented Reality and Knowledge-Based Systems in Maintaining Aircraft. Proc. of the Twenty-Sixth Annual Conference on Innovative Applications of Artificial Intelligence; 2014.

[11] Regenbrecht H, Baratoff G, Wilke W. Augmented Reality Projects in Automotive and Aerospace Industry. IEEE computer graphics and applications; 2005.

[12] Platonov J, Heibel H, Meier P, Grollmann B. A mobile markerless AR system for maintenance and repair. ISMAR '06 Proceedings of the 5th IEEE and ACM International Symposium on Mixed and Augmented Reality; 2006. p. 105-108.

[13] URL: http://www.armedia.it/i-mechanic. Date of access: March 2015.

[14] URL: http://www.designboom.com/technology/augmented-reality-car-repair-manual-for-google-glass-by-metaio. Date of access: April 2015.

[15] Fiorentino M, Uva AE, Gattullo M, Debernardis S, Monno G. Augmented reality on large screen for interactive maintenance instructions. Computers in Industry 65; 2014. p. 270–278.

[16] Wang X, Dunston PS, Skibniewski M. Mixed reality technology applications in construction equipment operator training. ISARC 21st Int. Symposium on Automation and Robotics in Construction; 2004.

[17] Klinker G, Creighton O, Dutoit AH, Kobylinski R, Vilsmeier C, Brügge B. Augmented maintenance of powerplants: A prototyping case study of a mobile AR system. Proceedings. IEEE and ACM International Symposium on Augmented Reality; 2001. p. 124 – 133.

[18] Goose S, Sudarsky S, Zhang X, Navab N. Speech-Enabled Augmented Reality Supporting Mobile Industrial Maintenance. Pervasive Computing, IEEE , Volume 2 , Issue 1; 2003. p. 65-70.

[19] Ke C, Kang B, Chen D, Li X. An Augmented Reality-Based Application for Equipment Maintenance. Lecture Notes in Computer Science, Volume 3784; 2005. p. 836-841.

[20] Schall G, Mendez E, Kruijff E, Veas E, Junghanns S, Reitinger B, Schmalstieg D. Handheld Augmented Reality for Underground Infrastructure Visualization. Personal and Ubiquitous Computing, Volume 13, Issue 4; 2009. p. 281-291.

[21] Henderson SJ, Feiner S. Evaluating the Benefits of Augmented Reality for Task Localization in Maintenance of an Armored Personnel Carrier Turret. IEEE Int. Symposium on Mixed and Augmented Reality; 2009.

[22] Martínez H, Fabry T, Laukkanen S, Mattila J, Tabourot L. Augmented reality aiding collimator exchange at the LHC. Nuclear Instruments and Methods in Physics Research A 763; 2014. p. 354–363.

[23] Datcu D, Cidota M, Lukosch S, Oliveira DM, Wolff M. Virtual Co-location to Support Remote Assistance for Inflight Maintenance in Ground Training for Space Missions. International Conference on Computer Systems and Technologies; 2014.

[24] Azpiazu J, Siltanen S, Multanen P, Mäkiranta A, Barrena N, Díez A, Agirre J, Smith T. Remote support for maintenance tasks by the use of

Augmented Reality: the ManuVAR project. 9th Congress on Virtual Reality Applications (CARVI); 2011.
[25] URL: http://www.the-eic.com/News/NewsStory/tabid/766/ArticleID/1838/Applus-RTD-introduces-Augmented-Reality-to-NDT.aspx Date of access: March 2015
[26] URL: http://www.testia.com/SMW-mira. Date of access: March 2015
[27] Wojcicki T. Supporting the diagnostics and the maintenance of technical devices with augmented reality. Diagnostyka Vol.15/1; 2014.
[28] URL: http://www.continental-automotive.com/diagnostics. Date of access: April 2015
[29] URL: http://www.re-flekt.com/en/automotive-ar/173-flex-inspect-en. Date of access: March 2015
[30] Dong S, Feng C, Kamat VR. Sensitivity analysis of augmented reality-assisted building damage reconnaissance using virtual prototyping. Automation in Construction 33; 2013. p. 24–36.
[31] De Crescenzio F, Fantini M. Implementing augmented reality to aircraft maintenance: a daily inspection case study. Proc. of IDMME; 2010.
[32] Hincapié M, Caponio A, Rios H, Mendívil EG. An Introduction to Augmented Reality with Applications in Aeronautical Maintenance. 13th International Conference on Transparent Optical Networks (ICTON); 2011. p. 1–4.
[33] Nakajima C, Itho N. A Support System for Maintenance Training by Augmented Reality. Proceedings of the 12th International Conference on Image Analysis and Processing; 2003.
[34] Behzadan AH, Kamat VR. Interactive Augmented Reality Visualization for Improved Damage Prevention and Maintenance of Underground Infrastructure. Proceedings of the 2009 Construction Research Congress; 2009.
[35] Olwal A, Gustafsson J, Lindfors C. Spatial augmented reality on industrial CNC-machines. Proc. of SPIE 2008 Electronic Imaging, Vol. 6804 (The Engineering Reality of Virtual Reality 2008); 2008.
[36] URL: http://cordis.europa.eu/result/rcn/59062_en.html. Date of access: April 2015
[37] Chimienti V, Iliano S, Dassisti M, Dini G, Failli F. Guidelines for implementing augmented reality procedures in assisting assembly operations. Proceedings of IPAS 2010; 2010.
[38] Iliano S, Chimienti V, Dini G. Training by augmented reality in industrial environments: a case study. Proc. of 4th CIRP Conf. on Assembly Technology and Systems, Ann Arbor; 2012.
[39] Dalle Mura M, Dini G, Failli F, An integrated environment based on augmented reality and sensing device for manual assembly worstations, Proc. of 48th CIRP Conf. on Manufacturing Systems CIRP CMS 2015, Ischia Island, 24-26 June 2015.