The Industrial Track of EuroVR 2018

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EuroVR 2018: London
22-23 October 2018

The Industrial Track of EuroVR 2018

Proceedings of the 15th Annual EuroVR Conference

Kaj Helin | Matthieu Poyade | Mirabelle D’Cruz |
Richard Eastgate (eds.)

VTT TECHNOLOGY 339

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EuroVR 2018: London

The focus of EuroVR 2018 is to present novel Virtual Reality (VR) up-to Mixed Reality (MR) technologies, including software systems, display technology, interaction devices, and applications. Besides papers on novel results, industry-oriented presentations (automotive, medical, etc.), the EuroVR conference series creates a unique opportunity for participants to network, discuss, and share the latest innovations around commercial and research applications.

As in previous years, we welcome industrial and academic exhibitors, as well as sponsors, all within the same exhibition area, to connect with our community.

Our major priority is to provide authors the opportunity to prestigiously disseminate their innovative work within the wide community of end-users, from large scale industries to SMEs.

October 22-23, 2018

London, UK

Conference organizers

Preface

We are pleased to present these conference proceedings in the VTT Technology series, the papers accepted for the Industrial Track of EuroVR 2018, the 15th annual EuroVR conference, Savoy Place, London, United Kingdom, 22nd to 23th October 2018.

In previous years the EuroVR conference has been held in Bremen (2014), Lecco (2015), Athens (2016), and Laval (2017). This series was initiated in 2004 by the INTUITION Network of Excellence in Virtual and Augmented Reality, supported by the European Commission until 2008, and incorporated within the Joint Virtual Reality Conferences (JVRC) from 2009 to 2013. The focus of the EuroVR conferences is to present, each year, novel Virtual Reality (VR), Mixed Reality (MR) and Augmented Reality (AR) technologies, including software systems, display technologies, interaction devices, and applications, to foster engagement between industry, academia, and the public sector, and to promote the development and deployment of VR/MR/AR technologies in new, emerging, and existing fields. This annual event of the EuroVR association (https://www.eurovr-association.org/) provides a unique platform for exchange between researchers, technology providers, and end users around commercial or research applications.

This publication is a collection of the industrial papers presented at the conference. It provides an interesting perspective into current and future industrial applications of VR/AR/MR. The Industrial Track is an opportunity for industry to tell the research and development communities what they use the technologies for, to say what they really think about VR/AR/MR, and to explain their needs now and in the future. You will find presentations from large and small industries from all over Europe and beyond.

We would like to warmly thank the industrial committee chairs for their great support and commitment to the conference, and special thanks go to the local organizing committee for their great effort in making this event happen ☺.

Enjoy your time in London!

On behalf of the organising committee,

Kaj Helin

VTT

EuroVR IPC member and Principal Scientist at VTT Technical Research Centre of Finland Ltd., Finland

Matthieu Poyade

SCHOOL OF SIMULATION AND VISUALISATION
THE GLASGOW SCHOOL OF ART

Research Fellow and Lecturer at School of Simulation and Visualisation, Glasgow School of Arts, UK

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EuroVR Industrial Chairs

- Kaj Helin (VTT, Finland)
- Jérome Perret (Haption, France & Germany)
- Rab Scott (Advance Manufacturing Research Centre, UK)
- Christoph Runde (VDC, Germany)
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- Joe Gabbard (Virginia Tech, USA)
- Chris Freeman (Advanced Manufacturing Research Centre/ High Value Manufacturing Catapult, UK)
- Matthieu Poyade (Glasgow School of Arts, UK)

Program overview

Program overview

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- Context-dependent Memory in Real and Virtual Reality (short paper)
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- Evaluating the Benefit of Assistive AR Technology through Eye Tracking in a Surgical Simulation System
  Jorge De Greef, Vladimir Poliakov, Caspar Gruijthuijsen, Allan Javaux, Mirza Awais Ahmad, Johan Philips, Sergio Portoles Diez and Emmanuel Vander Poorten

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15:45-16:30 Poster, Demo & Exhibit session

16:30-17:00 Awards Ceremony and Conference Close

Presentations

Immersive Applications of Industrial Digital Twins

Jonathan Eyre and Chris Freeman

Advanced Manufacturing Research Centre, Rotherdam, United Kingdom

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Keywords: digital twin, visualisation, monitoring, process, simulation, immersive, real-time, modelling, discrete event simulation, manufacturing

Abstract

Digital twins have received a large amount of exposure stating the value they can offer industry, generating lots of noise, however demonstrations that present industrial use cases are uncommon. Prototypes of the current state of the art are needed however for industry to be able to develop business cases to generate investment into the technology and understand the technical challenges for a robust production system. The AMRC have created several prototypes with industrial companies at different levels of industrial readiness using different methodologies. These vary from state information overlaid onto model information for monitoring through to a real-time closed-loop process digital twin utilising discrete event simulation.

Within three examples, the variety of development areas for different manufacturing sectors and applications for digital twins are presented. The first integrated existing data connectivity on top of a 3D visualisation. Another focuses on an immersive visualisation for greater realism within the Unreal Engine for the dual purpose of training scenarios as well as an emulated digital twin investigating if the higher-quality visualisation is an important aspect required for digital twins. The final example was developed for immersive virtual reality and split into the formation of a real-time monitoring digital twin driven by state information from a robotic control system and an extension to develop the software into a closed-loop process digital twin by using a discrete event simulation that is run in parallel. Overall, each prototype highlights a different approach to producing a digital twin with the commonality of producing an immersive environment to suit the application highlighting the varied nature of what is required for digital twins within different sectors.

Introduction

Digital twin is a term originally defined by Dr. Michael Grieves' in 2003 at the University of Michigan (Grieves, 2014), but has gained significance worldwide both within industry and academia for the virtualisation of assets. Fundamentally, a digital twin is a mimic of a real world asset displaying up to date information of what is currently happening. This article presents case studies investigating the benefit of immersive for digital twin applications, which although this definition does not require the use of 3D model information, an immersive digital twin does. Due to this, the case studies presented within this report exclusively investigates 3D models being used originating from Computer Aided Design (CAD).

Conventional CAD software packages are unsuitable for real-time viewing of an asset due to functionality to accept a live data feed not being incorporated into this type of software. Due to this, real-time visualisation software is required that has the capability of displaying content while incorporating a communication connection to external data sources. One range of software that fits these requirements is real-time engines, which are conventionally for creating and deploying games to a wide range of platforms. Using a real-time engine does cause some complications such as three-dimensional model data is required to be a triangular mesh, also known as a polygon mesh, rather than a CAD data format. Although polygon mesh formats can be produced from CAD software, these frequently contain too much information for real-time engines to handle and hence additional preparation is required of the model information. Due to this, immersive digital twins are more complex to produce and the value associated with them are often speculative.

Investments into immersive technologies for the manufacturing sector is increasing and those already utilising the technology are often seeing good return on investment. On the other hand, few digital twin examples are publicly available for discussion to understand the benefits with even fewer utilising immersive technologies. This may be due to the current hype cycle of where the technology stands at the time of writing, as shown in Figure 1. Digital twin is almost at the peak of inflate expectations where we are seeing some early adopters producing success stories, while others may be failing or not starting to invest at all. Although the anticipated *trough of disillusionment* is expected to start as interests diminish due to expectations not being met, there is value to be evaluated and characterised. This will allow those wanting to invest in production ready systems to have a greater chance of success with the expected return value being better understood beforehand, which is possible through the evaluation of prototypes such as those presented within this article.

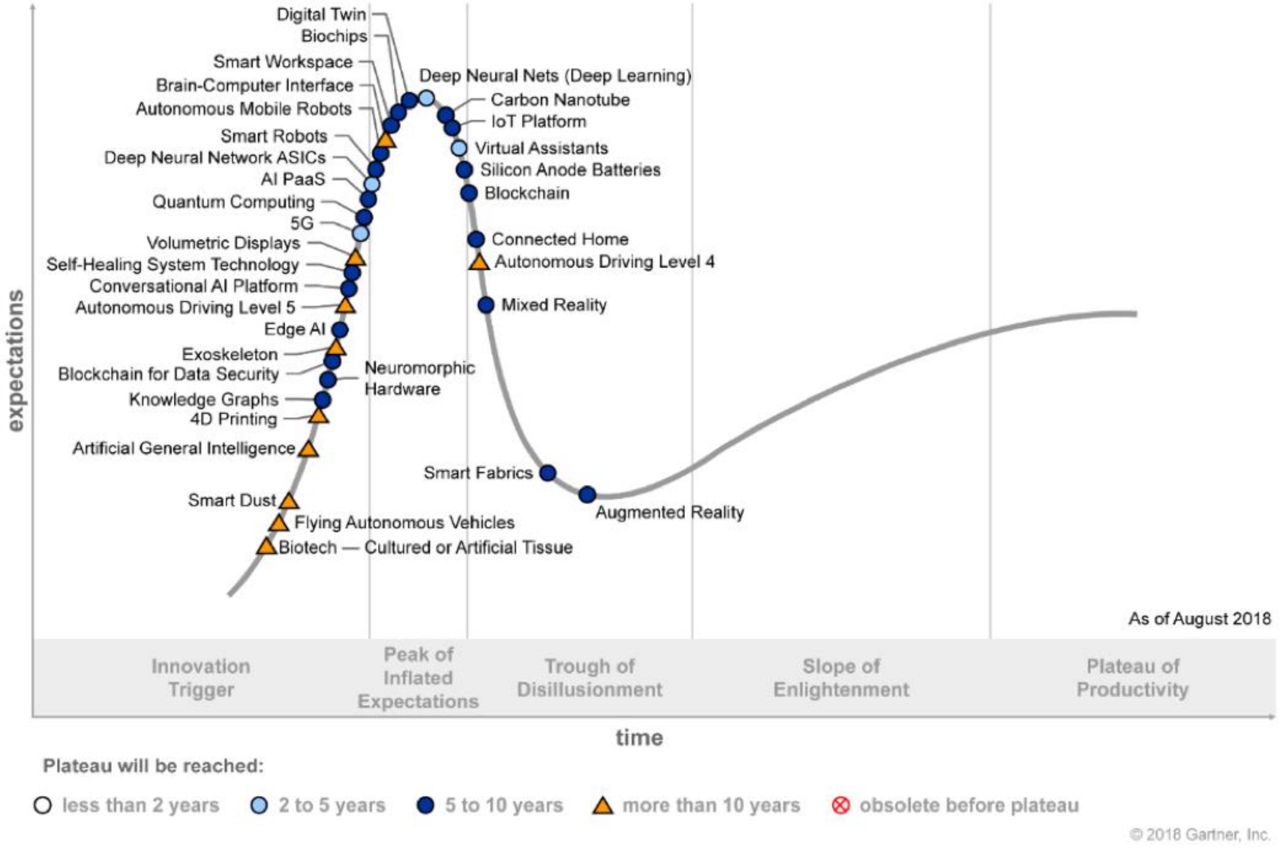


Figure 1. Hype cycle with digital twin at the top of the *peak of expectations*, August 2018 (Gartner, 2018).

Overall, this article presents three case studies of different digital twins to aid with the expectation of what digital twins mean to manufacturing. Although there are different types of digital twin, within this report only two monitoring digital twins and one process digital twin are presented due to the investigation of developed prototypes instead of theoretical solutions. The latter process digital twin not only provides a way to view real-time state information through core monitoring, but additionally simulates process information closing the real-time feedback loop of information to the user.

Data Overlay of Engineering Information

For industry that have already invested into remote monitoring applications, such as Hosokawa Micron Ltd, an immersive digital twin was the next step. From their previously developed dashboard application for remote monitoring, their customers could manage their manufacturing processes through their data capture and analysis system. With the data connection already available, information could be overlaid on virtual panels within an immersive world generated from their CAD model information.

This example prototype was one of Hosokawa's air classifier mill to monitor the current state of the mill in real-time with the vision of being able to respond to changes faster, make more informed decisions and improve efficiency (Hosokawa Micron Ltd, 2017) (Process Engineering, 2017). As they did not have the visualisation expertise in house, they worked with the AMRC to produce the prototype within Visionary Render, produced by Virtalis, to power their visualisation. Visionary Render allows 3D models to be used to generate immersive virtual reality (VR) environments created from one or multiple sources, which Hosokawa has already been investigating in other areas of the business. Visionary Render is aimed at engineers to both manipulate models and allow scripting of all elements in a scene, including labels of information that can be linked to a live data source. This was utilised in the prototype to produce labels of information at their respective model locations, Figure 2.

The value explored was the ability to contextual view information that is not possible from a list of control system tag names and values. Even within this small prototype, an engineer could look at what was down-stream or up-stream of a process that was performing inadequately to better understand the current working parameters, which was previously difficult to understand without first knowing the system.

Figure 2. Hosokawa Micron Ltd. monitoring digital twin of a air classifer mill.

Immersive Visualisation for Training and Monitoring

Immersive environments, such as the previous example, can be created in various software packages; Visionary Render is just one of those that are able to produce content of this nature. Another software package is the Unreal Engine produced by Epic Games, which is game engine with a suite of creation tools to create realistic environments typically for game creators. Although it is capable of producing more realistic visuals, it requires greater effort to produce. This may not be suitable for all digital twin applications as it may not be worth the investment required to produce and may even course information be harder to access, however other business use cases can utilise the greater realism produced.

One of these areas some sectors are investing into is training scenarios that require high-quality graphics within an immersive and more importantly, safe environment. One example was the development of an immersive virtual reality training module for tunnel boring machines between Thames Tideway, Ferrovian Agroman and Laing O'Rourke, Hobs Studio, AMRC, and AFRC (Innovate UK, 2018). The project was developed to enable training without being within the hazardous environment. The aim of this was to improve the health and safety for trainees and productivity by reducing machinery down time due it no longer being required for 'live' training overall reducing project costs. Training within the construction sector commonly involves a mix of: classroom presentations, 1:1 scale mock ups and on-site, with the last two having the greater expense.

The second half of the project investigated the value of a monitoring digital twin within the environment already developed by Hobs Media. Due to the scope of the project being investigative only, the data used was emulated around an extract of the provided control system tag information. A selection of tags were used to suit different user scenarios. One selected area was a conveyor section where the chosen information was deemed suitable for an engineer whose job role is to ensure the required performance of the machine is meeting the expected performance with the system behaving as anticipated. The five key tags presented for the conveyor are shown in Figure 3. Although a production system would also implement condition based monitoring around the data values to ensure they are all within limits, the experience of the staff and human ability to recognise trends when presented key live information allow the staff to recognise issues that the system hasn't picked up yet.

This approach was repeated for the cutter head to demonstrate this approach was suitable for other areas, which can be seen in Figure 4. Although the data presented is for an overview of the cutting head, as is the case with the conveyor, the indication is the presented tags would be the key parts an engineer would needed to be presented to maintain the TBM cutting head. The full tag list for the cutter head contains 103 tags that was deemed too much information to be shown at once for a user to quickly see the key data points about the status about the cutter head. This is one limitation within an immersive environment where information needs to either be displayed within the world space (diegetic) or as a user-interface on side panels (non-diegetic) and large lists of information are better suited for traditional HMIs.

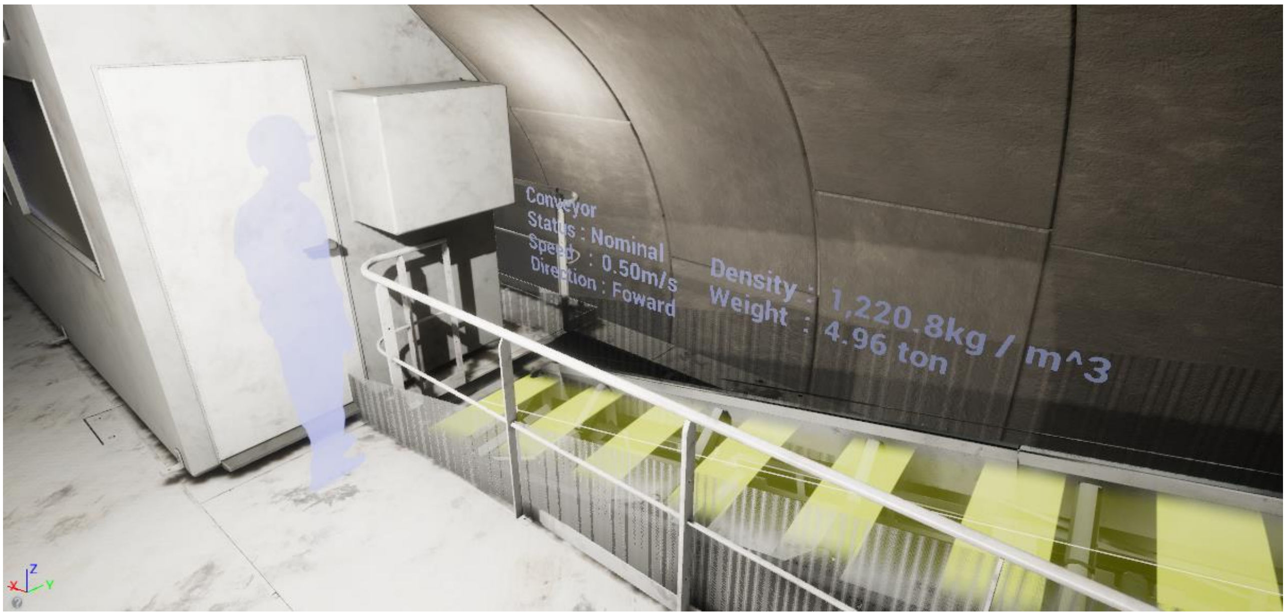


Figure 3. Display feed for monitoring the conveyor aimed towards a technical engineer.

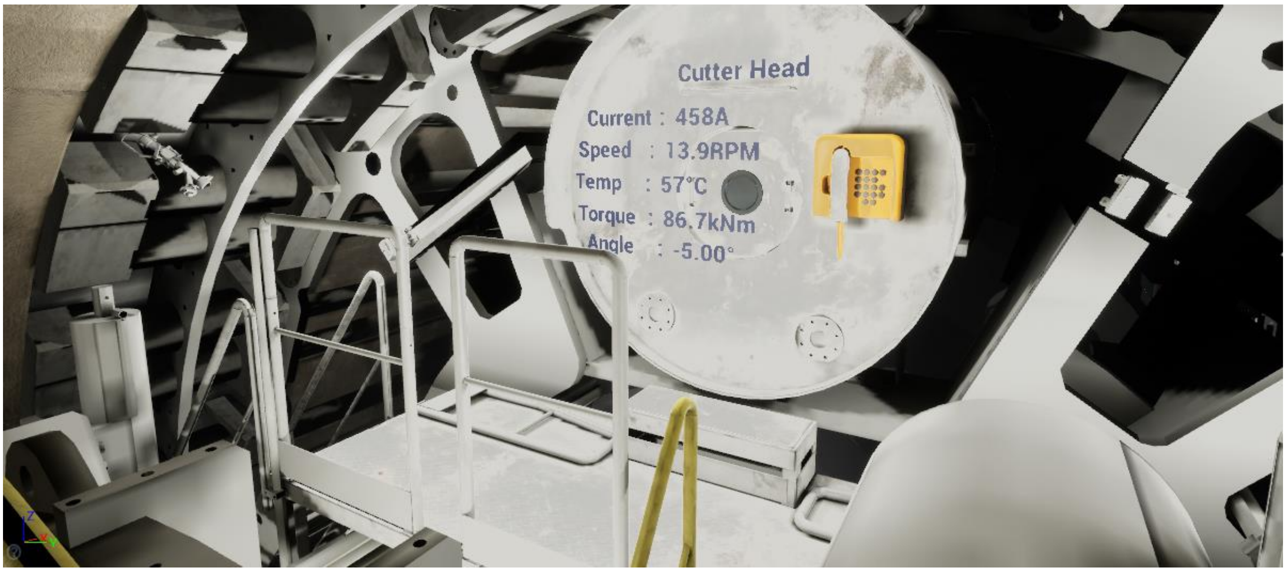


Figure 4. Display feed for the cutter head showing key overall values for the complete head.

A third dashboard area was created for a supervisory level role to be able to see all systems statuses with any discrepancy to be flagged up to be acted upon, which is shown in

Figure 5. This demonstrates the ability to display information for different users depending on the job role and their interest area.

Figure 5. The main overview for supervisors working on the TBM stating the main system statuses.

Overall, several key findings were found from the final demonstration. The primary result was several information sets don't need to be within an immersive environment. Supervisory level systems were preferred on a traditional desktop screen interface to easily see if the system is running okay. However, for areas where confusion could be found, such as which section of the conveyer was being discussed, it was found to be beneficial. On the other hand, once detail about that section was being discussed it was felt that little value was provided by the immersive environment over a traditional interface.

Closed Loop Process Digital Twin

The previous two examples presented monitoring applications, however the full value of a digital twin goes further. One development area augmenting monitoring is the integration of real-time simulation of processes transforming a monitoring digital twin into a process digital twin, which some companies are already starting to investigate. This allows the closing of a real-time viewing loop to provide extra contextual information to the viewer. Although monitoring has value alone, as shown within the first two prototypes, the simulation allows the user to make better informed decisions through two key areas. The first is prediction to forecast what is likely to happen in the future from current state and past performance. The second is simulating around these conditions to optimise the process to avoid unnecessary downtime to be able to make adjustments to the process and schedule with confidence. This manipulation of potential outcomes allows users to ask *what if* scenarios allowing more efficient and potentially exploring new ways of working. Both of these combined allow key decision makers to better understand the current and alternative ways of handling processes by not only simulating, but seeing the results within an immersive environment.

This concept of a process digital twin has been implemented on a reconfigurable fixture cell at the AMRC, Factory 2050. The simulation has been incorporate by developing a Discrete Event Simulation (DES) using key information about an existing process. The simulation was created in Siemens Plant Simulation that accesses information from the Siemens control system. The simulation replicates what is physically happening to provide information in real-time with the information being sent across the network to be viewable for any client connected within the digital twin software.

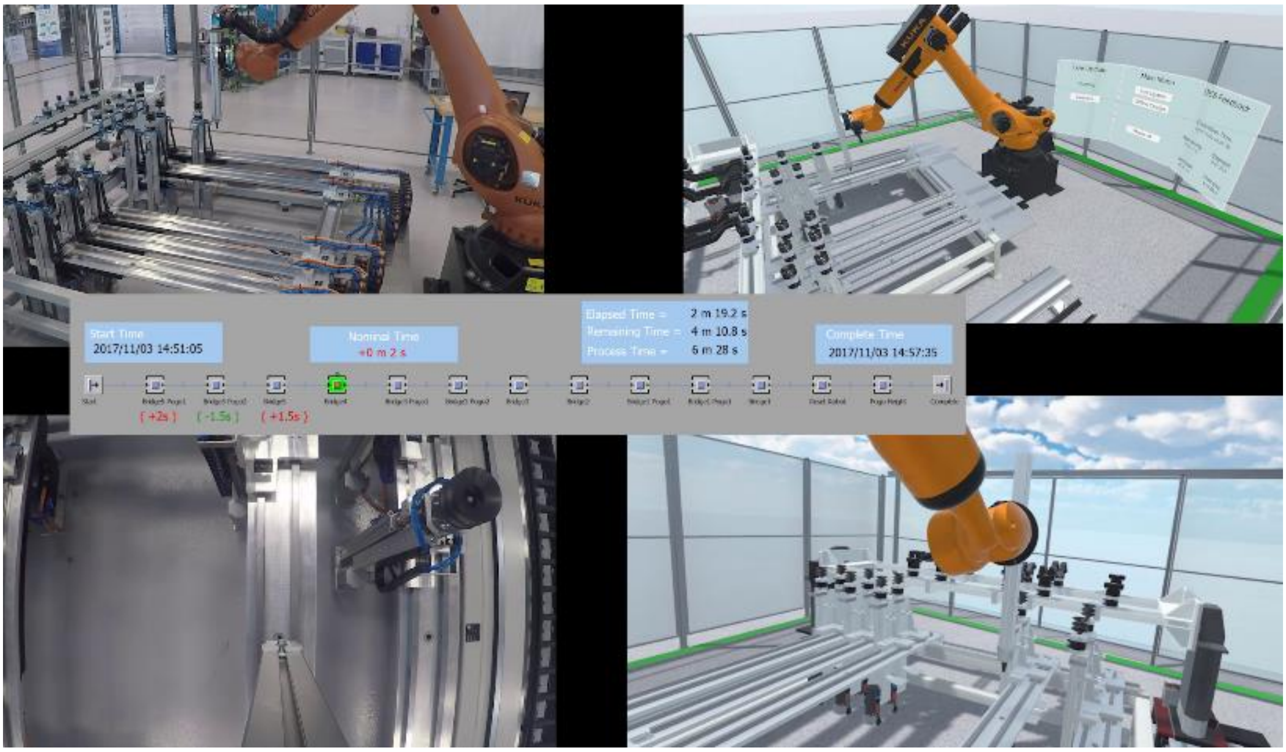
The development of this prototype was created within another real-time engine, Unity3D, which is similar to the Unreal Engine mentioned in the previous example. Both the previous two examples presented the state information of labels for the viewer to read the values and understand what they mean, however two other methods were investigated within this prototype to minimise the amount of text required. In addition, the application inspected the benefit of fully mimicking what would be seen if stood next to the cell. Overall the three methods of visualisation were:

Realistic positional and rotational movements utilising linear kinematics. This was used to transition models from their current state to new states utilising their maximum velocity and acceleration to match the real-system. This required additional development and more processing power for each connected client, however this leads to a more realistic result that adds to the immersion of the system.

Where toggle state information was only available two different methods were applied. To describe movements, such as the cell door sliding, a pre-specified animation cycle was triggered to either open or close. To describe other state changes, such as whether the cell safety stopped had been triggered, the material colours of an object in the scene were changed, such as red for triggered and requires resetting or green for okay.

Any remaining states were then implemented in the same methods previously, as graphical user interfaces (GUIs), such as those that been used to show the current state of the pneumatic lock states and process information that is driven from the DES simulation.

Figure 6 shows the final implementation of the digital twin with the real cell, DES simulation and process digital twin software mimicking the process. The real cell is shown on the left with an overall view (top left) and a top down view from the robot end effector (bottom left). The discrete event simulation software (middle) is displaying: the current state, start time, elapsed time, remaining time, process time, nominal time and expected completion time. This information is made available through a shop floor network, shown on a GUI within the digital twin providing additional information for the user to the current physical state of the system. This forms the feedback loop within the process digital twin providing real-time process information alongside real-time state information. The implemented concurrent simulation information allows a comparison from the current status of the cell to the expected.


Start Time
2017/11/03 14:51:05

Nominal Time
+0 m 2 s

Elapsed Time = 2 m 19.2 s
Remaining Time = 4 m 10.8 s
Process Time = 6 m 28 s

Complete Time
2017/11/03 14:57:35

Figure 6. Implementation of the digital twin showing the real cell (left), the discrete event simulation (middle) and an immersive digital twin within VR (right).

Conclusion

Digital twins are currently seen as something that is over hyped and few industrial demonstrators shown actual applications of them. In addition, they are also defined differently for many different people. Due to this, the value associated with them, in particular immersive applications of digital twin, are often hard to come across. Three examples have been presented and discussed displaying industrial use-cases of digital twins.

The first monitoring application produced with Hosokawa Micron Ltd. and the AMRC investigated the presentation for a monitoring application utilising data overlaid on engineer model information. The value presented was found to be within the contextualisation of the information so the viewer is able to relate the information panels to the item of interest.

The second prototype desired greater realism within an immersive environment for an emulated monitoring digital twin. Although produced primarily for health and safety training scenarios, the advanced visualisation permitted a study of when the complex environment was necessary. Although the environment helped provide greater immersion to understand the context of the information, feedback suggested further investigation should be carried out as it was thought it was not suitable for all information displays, in particular those for top level management and high detailed areas.

The final example showcased an immersive process digital twin that investigated two different notions: parallel discrete event simulation providing feedback to enable a closed feedback loop real-time process digital twin and utilisation of the state information to drive animations and visual changes within the environment. The latter is what adds to the value of creating an immersive environment, which added greater realism by driving visuals changes with animations moving items whilst minimised the amount of display panels required. Overall this created a cleaner environment and better immersion for the viewer, which although was more complex to set up, the feedback was positive stating it was practically a requirement when dealing with this type of information.

Overall, immersive digital twins have great value to add to the manufacturing sector. Although they require further investigation into quantifiable value for business cases for investments to be made, within two monitoring and a process digital twin, ascertainable benefits were established for all three use cases.

Acknowledgements

The author would like to thank the AMRC for supporting the writing of this paper. Secondly, Hosokawa Micron Ltd, Thames Tideway, Ferrovian Agroman and Laing O'Rourke, Hobs Studio and AFRC for their support during the development of the projects whilst in development with the AMRC.

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AR Guidance for Trauma Surgery in Austere Environments

Dan Andersen[1], Edgar Rojas-Muñoz[1], Chengyuan Lin[1], Maria Eugenia Cabrera[1], Voicu Popescu[1], Sherri Marley[2], Kathryn Anderson[2], Ben Zarzaur[2], Brian Mullis[2] and Juan Wachs[1]

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Keywords: augmented reality, surgical telementoring, telemedicine.

Trauma injuries in austere environments, such as combat zones, developing countries, or rural settings, often require urgent and subspecialty surgical expertise that is not physically present. Surgical telementoring connects local generalist surgeons with remote expert mentors during a procedure to improve patient outcomes. However, traditional telementoring solutions rely on telestrators, which display a mentor's visual instructions onto a nearby monitor. This increases cognitive load for the local mentee surgeon who must shift focus from the operating field and mentally remap the viewed instructions onto the patient's body.

Our project, STAR (System for Telementoring with Augmented Reality), bridges this gap by taking advantage of augmented reality (AR), which enables in-context superimposed visual annotations directly onto the patient's body. Our interdisciplinary team, comprised of computer scientists, industrial engineers, trauma surgeons, and nursing educators, has investigated, prototyped, and validated several AR-based telementoring solutions. Our first approach delivers mentor annotations using a conventional tablet, which offers pixel-level alignment with the operating field, while our second approach instead uses an AR HMD, which offers additional portability, surgeon mobility, and stereo rendering.

In our tablet-based AR telementoring system, the mentee surgeon views the operating field through a video see-through tablet suspended over the patient's body (Figure 1, left). Live video imagery from the tablet is transmitted to the mentor, who uses a touch-screen interaction table to author annotations in the form of lines, points, icons of surgical instruments, and prerecorded video footage. Annotations are transmitted back to the mentee site, where they appear directly in the mentee's field of view superimposed onto the operating field elements they describe (Figure 1, right). In a user study in which subjects performed an abdominal incision on a patient simulator under telementored guidance, such tablet-based telementoring led to increased accuracy and fewer focus shifts than conventional telestration.

Figure 1. Left: A mentee views the operating field of a patient simulator through our tablet-based AR system. Right: View of operating field with visual annotations (virtual hand) superimposed.

Figure 2. Left: Our AR HMD-based telementoring system being worn by the mentee. Right: First-person view of mentor-authored annotations (virtual instruments) anchored to the operating field.

Our AR HMD-based telementoring system uses a Microsoft HoloLens worn by the mentee surgeon, through which a direct view of the operating field can be seen (Figure 2, left). Video of the operating field, either from a calibrated overhead camera at the mentee site, or from the HMD's on-board camera, is pose-stabilized and streamed to the mentor using WebRTC bandwidth-adaptive protocols. Mentor-generated annotations are rendered as 3D models of surgical instruments that are anchored to the patient’s body (Figure 2, right). In a user study, medical students performed fasciotomies on cadaver legs under remote guidance using our system. Participants using our system, when compared against a control group without telementoring, made fewer errors, scored higher on performance metrics by expert evaluators, and completed the procedure in less time.

Our team is researching additional methods of augmenting both mentor and mentee surgical abilities and communication, such as overlaying data from a hand-held ultrasound device in AR, integrating an autonomous drone to provide the mentor with additional views of the operating field, and offering an immersive VR-based interface for mentors to view and author annotations in full 3D.

Acknowledgements

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Augmented Reality based Rover Maintenance in Mars/Moon Terrain Demonstrator

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Keywords: Augmented Reality, Work Support, Space Domain

Introduction

This industrial paper introduces the work done within the WEKIT - Wearable Experience for Knowledge Intensive Training – project. WEKIT is a three years project funded by the European Commission under the H2020 programme. It aims at creating an AR-based technological platform and an industry-focused learning methodology, then to widely share its methods and research findings and make them part of a repertoire of Europe's communities in Technology-Enhanced Learning (e.g. content developers, trainers) and end-users (e.g. in Industries). WEKIT exploits Augmented training in situ with live expert guidance capturing tacit learning experience with Wearable Technology (WT) and re-enactment of the expert with Augmented Reality (AR). The project is supported by three Industrial Cases: (1) Aircraft maintenance: exploiting AR and WT for inspection, decision making and safety; (2) Healthcare: exploiting AR and WT for improving innovation in technology and responsibility in healthcare applications and medical imaging; (3) Space: exploiting AR for astronauts training and for supporting the Mars rover maintenance. In this paper, we will focus on the second evaluation cycle of space Industrial case.

Evaluation case of the WEKIT AR-player

Working in the space domain means working in a complex and challenging domain, dealing with huge amount of datasets and several actors (engineers, scientists, discipline experts, etc.). To fully exploit people's know-how and all the available data, it is necessary to find a way to ease the communication and collaboration among the actors involved and at the same time to support the knowledge transfer. The scenario identified for the WEKIT space case is to check the status of the rover (damages, functionalities, etc.) and charge the battery. Also, during the execution of the procedure, unexpected errors triggered by sensor data shall be handled.

The second iteration of the WEKIT AR-player (Helin, 2017) the trial and evaluation phase will be ended by October 2018. The WEKIT space case was tested at ALTEC facility (Turin, Italy) performing a futuristic astronaut procedure on a physical mock-up of Mars Rover in Mars/Moon Terrain Demonstrator. More than 100 subjects were testing the system during 3 months period. Data and feedback from the participants were collected by means of a questionnaire composed by several sections (Learning Model, Technology Acceptance Model, the Spatial User Interface of AR, and System Usability Scale) and some additional questions that were asked to a smaller subgroup of the participants in order to get a more comprehensive feedback on their experience.

Figure 1. Left: Mars rover in Mars/Moon terrain simulator. Left: Video in 3D space for task support

Evaluation results

During the first trial campaign held on May 2017, the WEKIT AR-players usability had reached a reasonable level (average System Usability Scale - SUS score 68), both the pragmatic and emotional aspects of the user experience were considered fulfilling. It can be suggested that the AR-system is potentially a useful tool for supporting and facilitating the assembly and training procedure in the space field, even though the tool is still in prototyping phase (Vizzi et al., 2017). Preliminary results from the second trials shows that usability of system has been increased as AR-player has updated based on feedback from the first trials such as card user interface, orange guiding lines in 3D space, and all functions are working with gestures, voice commands and via button. Detailed results will be shown in the conference presentation.

Acknowledgements

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Appendix

Video from the second trials: https://youtu.be/JRMLs9SYg6k

Enabling the Teaching Factory leveraging a Virtual Reality system based on the Digital Twin

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Keywords: Teaching Factory; Virtual Reality; E-learning; Digital Twin; Cyber-Physical Systems.

Introduction

In the era of Industry 4.0, modern factories workers have to become resilient to the changing market conditions and to the complexity of new technologies involved in the production process. This means that workforce’s skills and competencies necessitate to be aligned to the changing needs of modern manufacturing companies. One of the promising paradigm moving in this direction is the Teaching Factory (Chryssolouris, 2016). Within this frame, the factory becomes a life-long learning educational places, where, by leveraging the newest ICT technologies together with instructional approaches oriented to learning-by-doing and authentic learning, human resources are kept up with the challenges involved in every day industrial practice (Caldarola, 2018).

Technology and in particular Information and Communication Technologies (ICTs) can play a significant role in realizing the Teaching Factory. Potentially, all the technological panorama related with Industry 4.0 is enabling for the Teaching Factory (Hermann, 2016). In this study, it is investigated the potential of the combination of two of these technologies, i.e., Virtual Reality (Ohta, 2014) and Digital Twin (Modoni, 2016). They are combined together to realize an interactive and explorative Virtual-Reality system, which aims at enhancing the human resources competencies and skills within the context of Industry 4.0, leveraging the capabilities of the Digital Twin fully synchronized with the Real Factory (Kutz, 2017) (Modoni, 2018).

Figure 1 presents the three different technologies, which come from the inspiring paradigms acknowledged in this work: the *Teaching Factory*, which is supported by e-learning or e-enhanced learning methodologies; the *Visual-based Manufacturing*, which is supported by *Mixed-Reality* or *Virtual-Reality* (MR/VR) applications and tools, together with intelligent human-computer interaction systems; and, finally, the *Digital Twin*, i.e., the implementation of a digital replica of the Real Factory, properly synchronized with the latter, allowing many benefits enhancing the production process. For each of the three technologies, Figure 1 also mentions a list of the major related enablers.

This paper introduces a Virtual-Reality system which represents our concrete realization of Teaching Factory paradigm. Specifically, the system consists in an interactive and explorative Virtual Reality environment which faithfully reproduce the physical factory and is fully synchronized with the latter, thus allowing to support a learning by doing approach set in a realistic context. A real case study is introduced and a concrete instance of the envisioned architecture is implemented in order to demonstrate the correctness and validity of the proposed system. The overall goal of the proposed system is exploring better and more efficient means to develop an awareness campaign to Industry 4.0 technologies and to reduce skills imbalances in these new technologies, as expected from different government and private institutions. Training in realistic manufacturing environments, bringing the learning process closer to the industrial practice, and leveraging practice through the adoption of new manufacturing knowledge, can improve young future engineers competences (Abele, 2015).

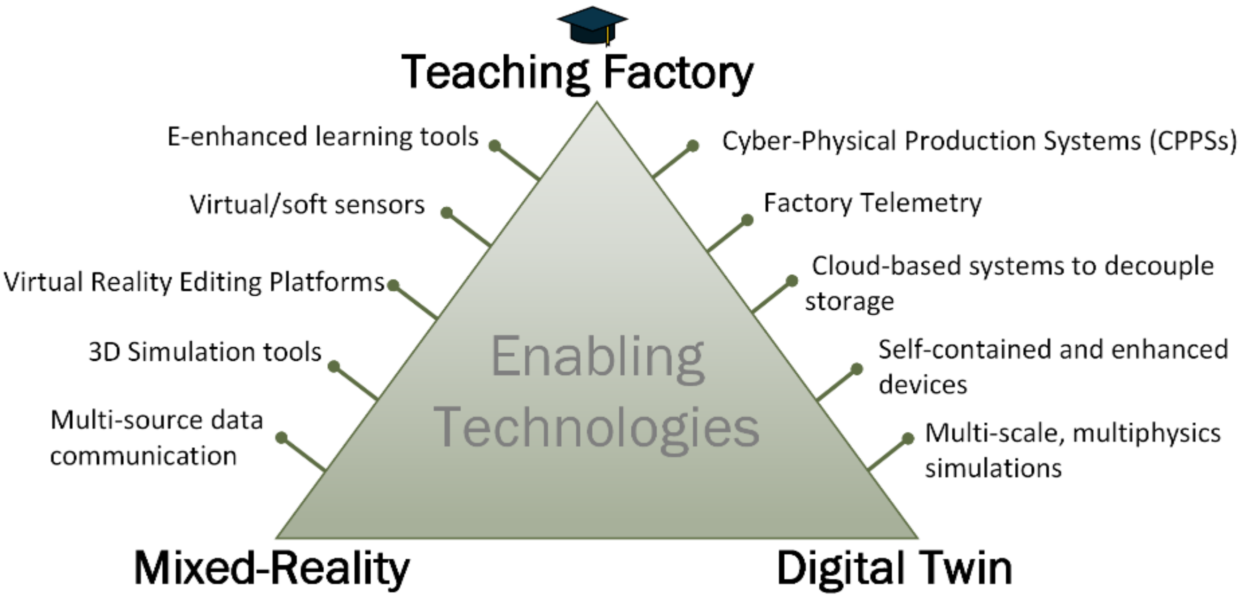

Figure 1. Teaching Factory supported by the Digital Twin and Mixed-Reality.

The Virtual Environment enabling the Teaching Factory: a case study

The Virtual-Reality system proposed in this paper has been implemented in the Flexible Manufacturing Systems (FMS) and Robotics Demo Centre of the Tallinn University of Technology. The latter is composed by the following four major parts (Figure 2):

- The Flexible Manufacturing Systems (FMS), which includes an automotive stock, a mobile delivery robot, a conveyor, the Mitsubishi robot and CNC machine (Figure 3). All such equipment are controlled by the Manufacturing Execution System (MES);
- The Monitoring and performance evaluation system endowed with Internet of Things (IoT) devices distributed on every hardware equipment. In addition, the provided system uses a cloud-based platform to handle statistics of different factors such as: energy waste, realized products count and so forth, for future use;
- The Industrial Robotics (IR) section, which consists of two heavy load robots. One is Yaskawa Motoman GP8 with a changeable tool for picking and placing tasks. The second is a ABB IRB1600 1.2 which is endowed with a 3D Nikon Laser scanner for inspection and measurement tasks (Kuts, 2016);
- The Virtual and Augmented Reality laboratory (IVAR lab), which consistsof: 1 5x4m VR zone, 2 HTC Vive sets and 1 Oculus Rift DK2 set (VRglasses), 1 Meta2 Augmented Reality (AR) set; 1 ManusVR haptic gloves,1 Vuzix M300 AR glasses (like Google Glass), 1 360-degrees camera and 1drone equipped with a camera.

The IVAR lab team is investigating in a case study the potential of VR paired with the Digital Twin to implement the Teaching Factory. Specifically, the study introduces a 3D virtual replica, in scale 1 to 1, of different types of equipment (robots, FMS, furniture) distributed in the manufacturing system of the Demo Center. These replicas can contribute to give to the user a great perception and feeling about the robots task execution processes, about CNC machine and mobile robot behaviour, providing realistic interactions of the machines near or with humans. In this scenario, the Virtual Reality environment is endowed with a full-body avatar (Figure 4) in optional multiplayer session allowing to re-program the equipment from digital world, to learn about human machine interaction in safe manner and to learn how-to use and be aware of the limits of the hardware. Optional multiplayer option can be used to simulate the presence of a trainer with one or more trainees, using full-body avatars (Figure 4) for better presence and social co-work aspect visualization. Instructions for the calibration and configuration of all the equipment can be superimposed in the virtual world through interactive pop-up user interfaces which support every step of the process.

Moreover, in order to manage the information concerning the real machines (e.g. configuration, state, etc.), the VR environment leverages a Digital Twin, fully synchronized with the real factory. Moreover, the Virtual Reality system, implemented through Unity 3D, recreates virtually all components which are not easily reproducible in the real environment, thus saving the time wasted for their production. The Virtual Reality system is paired with Factory Telemetry, i.e. data produced by the real machines and persisted into the Digital Twin to be used later to make more realistic the interaction of the user with the MR environment (Kuts, 2017) (Modoni, 2014). Indeed, these historical data can be used to simulate parts or the whole machines behaviour, by play backing and passing it as input to the control system of the simulated component (either real or virtual) (Caldarola, 2016).

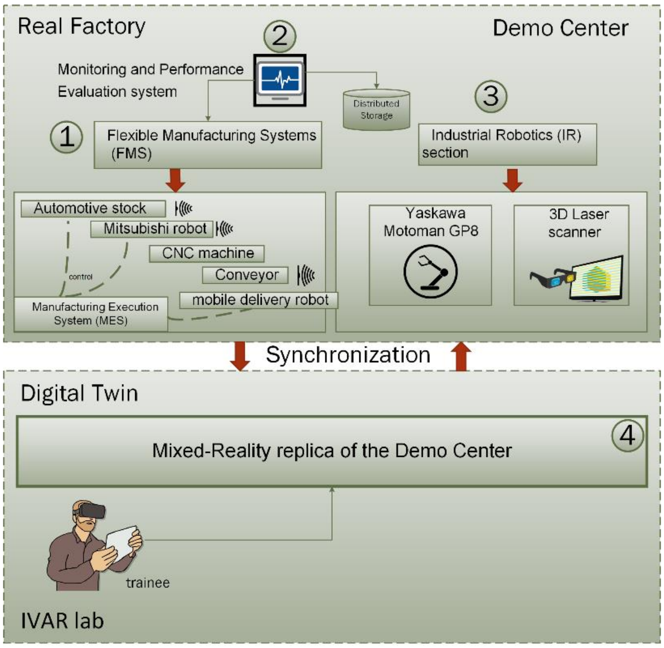

Figure 2. Demo center main components at Virtual Reality Lab University of Tallinn.

Moreover, in order to manage the information concerning the real machines (e.g. configuration, state, etc.), the VR environment leverages a Digital Twin, fully synchronized with the real factory. Moreover, the Virtual Reality system, implemented through Unity 3D, recreates virtually all components which are not easily reproducible in the real environment, thus saving the time wasted for their production. The Virtual Reality system is paired with Factory Telemetry, i.e. data produced by the real machines and persisted into the Digital Twin to be used later to make more realistic the interaction of the user with the MR environment (Kuts, 2017) (Modoni, 2014). Indeed, these historical data can be used to simulate parts or the whole machines behaviour, by play backing and passing it as input to the control system of the simulated component (either real or virtual) (Caldarola, 2016).

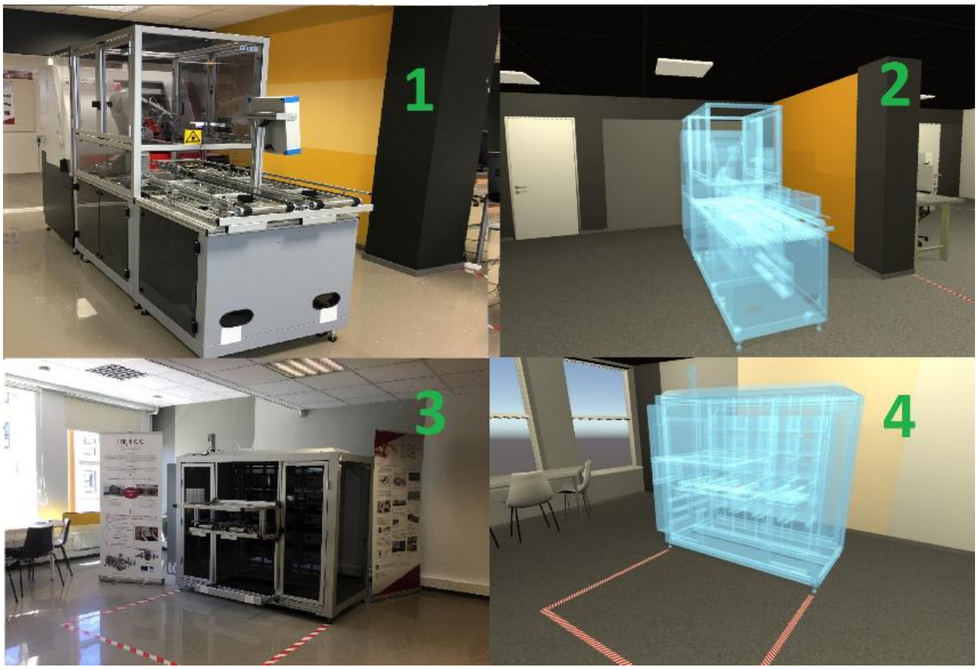

Figure 3. FMS system: Conveyor, robot and CNC machine 1) Real, 2) Virtual; Automo-tive stock: 3) Real, 4) Virtua.

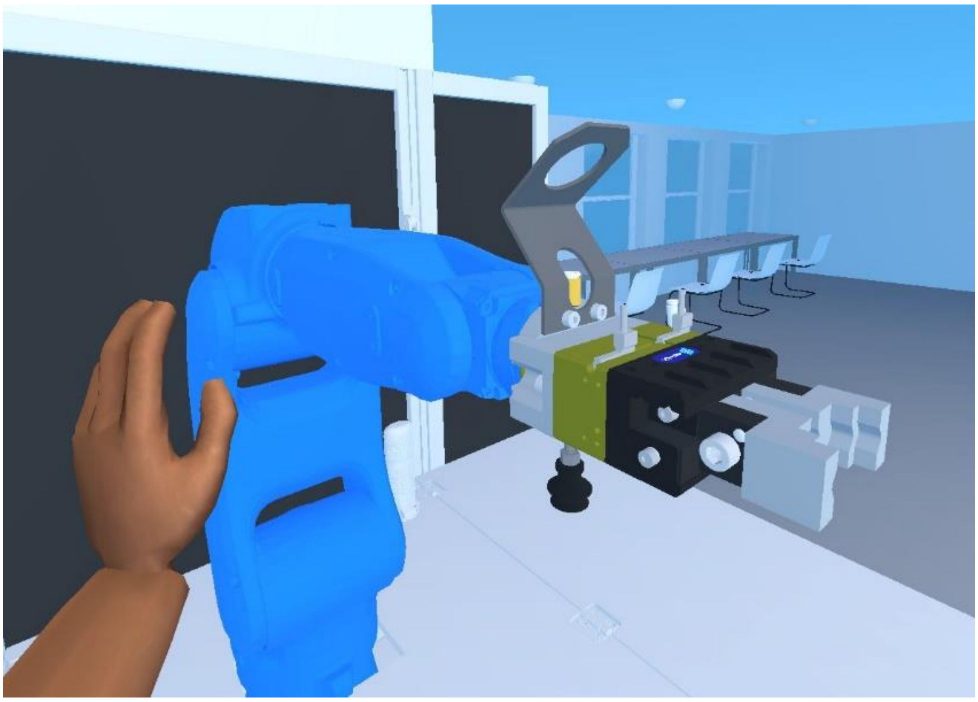

Figure 4. Yaskawa Motoman GP8 virtual replica used in the VR lab with trainee full-body avatar hand.

Conclusions

In this work, a virtual reality system has been proposed in order to enhance the continuous training and skills of workers within the Teaching Factory context. The conceived system leverages some of the cutting edge technologies belonging to the panorama of Industry 4.0, in particular those concerning Virtual-Reality, Digital Twin. Through an effective Teaching Factory, it is possible to demonstrate a facilitation of the alignment between the needs of modern factories and new competencies and skills workers need for contributing to make modern companies more resilient w.r.t. changes in market condition and desiderata. This work has also proposed a study case, whose scope is to demonstrate the advantages, in terms of performances and return of investments, that workers can gain from the adoption of the sponsored technologies, which have proven great successful in guaranteeing retention of knowledge and developing authentic competences. Future lines of researches will go in the direction of enlarging the set of study cases with the adoption of more sophisticated and complete knowledge models of the smart factory also by applying the proposed system to other industrial scenario and by creation of a middle-ware API platform for plug-and-play connectivity of the real and virtual worlds. Furthermore, we expect to face some of the challenges outlined in this work in implementing an effective Teaching Factory, for example, the prompt synchronization of the Digital Twin with respect to changes in the production process system. Moreover, additional VR perception and haptic technologies will be integrated to the use-cases to increase trainees perception capabilities in digital world.

Acknowledgements

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Evaluating the Benefit of Assistive AR Technology through Eye Tracking in a Surgical Simulation System

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Keywords: eye tracking, augmented reality, surgical training, surgical simulation, assistive technology

Introduction

General Background

Modern surgery evolves rapidly towards minimal invasive surgery (MIS) where an increased number of procedures are performed through small-sized incisions, so-called, keyholes, made into the body. The surgeon introduces long and slender instruments through these keyholes and operates under visual feedback from a camera (endoscope) that is introduced through one of the keyholes. This technique is highly beneficial for the patient who, in general, suffers less, has smaller scars and recovers faster. For the surgeon these procedures are more difficult to execute. It takes considerable time to become proficient. Vickers *et al.* reported a learning curve between 250-350 procedures for radical minimal invasive prostatectomy (Vickers, 2009).

Robotics and assistive technology have been introduced to simplify MIS, but the development and associated cost is significant. Furthermore, there is little room for experimenting as for every small adjustment or addition, a long regulatory and accommodation process follows. Virtual and physical simulators can help speeding up the design process. These systems, and especially the virtual simulators, can help keep the cost for validation of new instruments, novel assistive techniques or robotics lower, as validation can take place *before* actually creating a physical embodiment of an instrument or mechanism. This work further explores *eye tracking* as a technology to help validate new developments in a dedicated trainer for a surgical procedure to treat the Twin-to-Twin Transfusion Syndrome (TTTS) a fetal complication affecting 15% of monochorionic twins.

The paper is built up as follows. After surveying the state-of-the-art of eye tracking for similar applications in subsection 1.2, the setup of the proposed system is introduced in section 2. Experiments are described and discussed in section 3. Finally, a concluding section 4 wraps up this report.

Eye tracking for validation of assistive AR

The aim of eye tracking is to acquire the vector of gaze and/or the movement trajectory of the eyes of the person who is observed. Eye tracking has been used by researchers to estimate cognitive processes for over 30 years now. At its early stages, eye tracking put a lot of restrictions on the person under investigation, affecting the reliability of estimation. For instance, the Yarbus recording device, one of the first devices for eye tracking, required the head of the subject to be completely fixed (Tatler, 2010). Nevertheless, technology has become more sophisticated and less intrusive since then, enabling real-time gaze estimation without affecting the process the person is performing.

At present, eye tracking has become a method that is mature enough for considering its use in training programs to help evaluate the progress of trainees. In combination with AR, MR and VR training systems, eye tracking allows a tutor to understand where the attention of the trainee is concentrated upon, thus opening up possibilities to interactively correct actions during a session or through post-processing provide more in-depth analysis and feedback. Eye tracking may also help controlling the user’s gaze as it can initiate actions to re-focus to key points of the program. This approach is widely used in VR training and is reported to significantly decrease the learning curve. Wilson *et al.* proposed gaze tutoring as an alternative to movement tutoring. In the study, they compared learning curves of three groups: free-to-discovery subjects, who were free to discover how to solve the task on their own; gaze-trained subjects, who were shown a video of an expert performing the task with a footage of his visual control obtained from the eye tracker; and movement-trained subjects, who were shown the same video, but without a footage of visual control. Gaze-trained participants completed the tasks 55% faster, whereas movement-trained subjects only experienced a 32% reduction (Wilson, 2011). Ferrari *et al.* reports using eye tracking based navigation to maintain the attention of the student in an attention bias modification study. The study aimed to change the selective attention of participants by letting them perform a series of trials, where their attention was controlled and navigated by eye tracking (Ferrari, 2016). Chetwood *et al.* propose the use of eye tracking navigation to train laparoscopic surgery. This approach is based on collaborative eye tracking, where the point of regard of the supervisor is projected on the laparoscopic screen of the trainee, thus providing real-time guidance (Chetwood, 2011).

Another important use for eye tracking is as a validation tool of the study program itself, such as interface design, cues effectiveness, etc. Multiple studies report increase in efficiency of user interfaces (UI) with the help of eye tracking validation. Barkana *et al.* used eye tracking to improve the surgical interface for kidney tumor cryoablation. Through eye tracking the decision-making process can be halved (Barkana, 2013). Toni *et al.* validated a pediatric patient training system investigating the effect of using life-like animations of patients and identifying the most optimal layout to attract attention to keypoint areas (Toni, 2014).

Along similar lines in this work, eye tracking is used to evaluate the benefit of novel guidance information that is displayed on the user's screen. The running hypothesis would be that if trained surgeons make use of this guidance information while conducting the experiments, this would mean that it could be useful to consider incorporating this guidance information in the real world as well.

System Overview

Virtual TTTS simulator

The setup of the TTTS trainer can be seen in Figure 1. On the right, a robotic arm representing a fetoscope with embedded laser fiber can be seen. The trainee is to introduce this fetoscope through a narrow incision into the patient's uterus. He/she is to navigate the instrument to the placenta and is to laser ablate a number of vessel on the placental surface. A foot pedal positioned below the table is pushed to activate the laser. The user input (instrument motion and pedal state) is transferred to the simulation where the view, as seen by the fetoscope, is updated. The simulated view is visible on the left of Figure 1. This setup closely resembles the layout in a conventional TTTS surgery. As such a trainee can get used to the movements that would need to be made during a real intervention. Because the placenta can be in difficult to reach locations, the instrument might be turned in such a way that movements and the way they are seen on screen are not intuitive anymore. This is one of the main challenges that makes this surgery very difficult to perform.

An attempt is made to recreate an environment that visually resembles the reality closely. One particularly complex part of the operation is the limited visibility because of working within the amniotic fluid. This creates a grey fog-like effect. There is one light source available with controllable intensity that is used to illuminate the scene. A circular dot in the centre of the camera view represents the location of the laser. The pointing laser works as an aiming mechanism for coagulation in reality and has thus the same function in the simulator. When the pedal is pressed, coagulation takes place. The trainee will see a white burn mark on the surface. The area and intensity of this burn grows proportional to the time that the pedal is pressed.

Several settings are foreseen to adapt the scene for a specific type of surgical scenario. For example, the light intensity of the scene can be increased or decreased, the turbidity of the amniotic fluid and the presence of floating particles can be controlled to make the training task more challenging or more closely approach a real-world scenario. Since the placenta can be in many different positions, one can place the placenta at a desired position. All the settings can be saved into a file on the system and loaded at a later time.

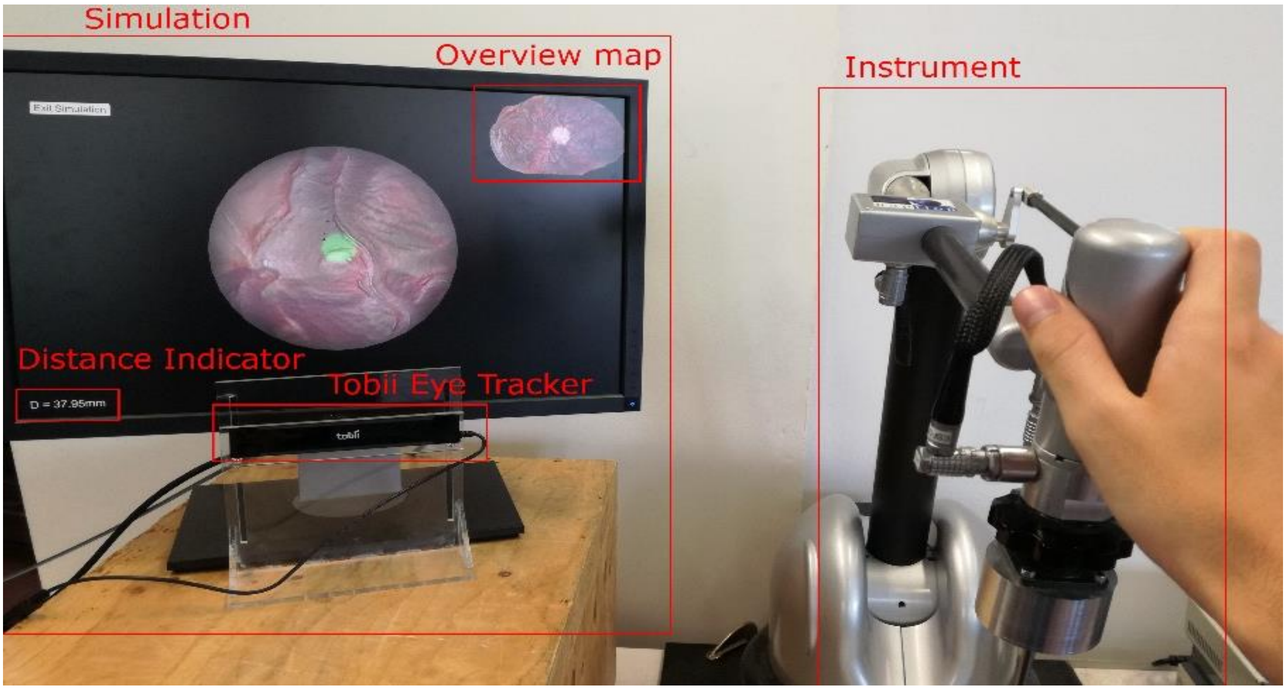

Figure 1. Setup of TTTS trainer; left: screen with eye tracker and visual cues; right: fetoscope handle simulated by the handle of a robotic arm that tracks the user movements; not visible foot pedal below the table.

There are two modes available, a free mode and a training mode. The free mode is meant to be used by a trainer who can investigate a set of the settings and save them. The trainer can use this mode to design training tasks. He/she can use the task menu and his/her mouse to place circles the trainee will then have to laser and then connect them by a continuous ablation path. Another task is designed as follows: upon placing a circle a random letter is inscribed in the circle. The trainee will then have to ablate circles following a sequence of letters. When one target has been coagulated satisfactorily, the next letter in the sequence, appears as it was inscribed. The different settings and tasks can be loaded in the training mode where these settings cannot be altered.

Eye tracking is being implemented to analyse how much the user is looking at certain areas of the screen. Especially it is used to see if the assistive features of the simulation are being used, whether they have no effect at all or whether they are even distracting to the user. These features are explained next.

Assistive technology under test.

There are two features under test: *1)* an indicator that reports the distance between the instrument tip and the placenta; *2)* a map that provides an overview of the placenta. Both features can be seen on in the respectively left bottom and right upper corner of the screen. At present this information is not available to the surgeon, but the distance could be measured by a dedicated sensor that could be embedded in the fetoscope and the map could be created online by a so-called mosaicking algorithm that stacks small-sized images taken from the fetoscope and builds these – much like a mosaic – up to a large placental image.

The distance information is important the instrument is sharp and one should at all cost try to avoid piercing it through the placenta. At such time the operation would be considered to have failed as the visibility will be completely blocked by the blood that comes free. Secondly, an ideal distance to laser anastomoses is estimated to be about 10 mm distance, the distance information could simplify maintaining this distance.

During a surgery, the surgeon has to memorise the points that have to be treated with the laser and remember the points that have been treated. By simply displaying this information on an overview map this task could become much easier. The map could also help planning the navigation to next targets.

These features are not available in surgery today. Their success and popularity will depend on whether the surgeon will take the liberty to adjust his gaze during the intervention to observe these features. To avoid finding this out in the operating room after a huge development investment, here we propose to use a virtual simulator to investigate the said features and to make a more profound decision regarding their potential and the value of further developing them. In the following section experiments built around a Tobii X2-30 Compact eye tracker are described.

Experiments

Description of the experimental protocol

First, a short analysis of the eye tracker's accuracy was performed. The accuracy depends both on the distance to the person as well as on the gaze angle, the angle between tracker and user's gaze. First, the tracker has to be calibrated using Tobii's calibration tool to get an accurate tracking. The error after this calibration is documented in the user's manual of Tobii (Tobii Technology AB14). The user will be at a 60 – 65 cm distance, resulting in a gaze angle accuracy of 0,2° to 0,6°. The gaze angle accuracy is reported to be same for ideal conditions up to a 30° angle, this gives an accuracy of 0,5°. Angles further than 30° are not listed, but Tobii states the angle should not exceed 36° to gain optimal tracking. A 24 inch monitor is used with a 16:10 aspect ratio which is reported as to fall within this 36° angle limit. So the maximum tracking error that can be expected would be approximately 1,1° by adding both errors. An experiment was designed to confirm the accuracy of the tracker experimentally. The user is asked to look at different targets with known pixel coordinate, tracking coordinates are collected and a root mean square (RMS) error calculated.

After confirming the accuracy, the experiments of the value of the assistive features during TTTS surgery are performed. A singular researcher, who has prior experience with fetoscopy, was used to perform these experiments. The two different tasks that are to be performed are described in section 0. The user does not need to identify the anastomoses, one can simply search and follow the targets that are placed on the provided placenta image. Five different experiments are conducted: three tasks consist of lasering circles and connecting them by a path (further mentioned as "Lines"), for the other two the user needs to laser targets in a sequential order (further called "Seq"). While the task is being performed an eye tracker mounted at the bottom of the screen is used to estimate what the user is looking at. This information is then analysed. The percentage of time spent looking at a certain user interface elements is computed. Secondly, a *heatmap* is created that provides a visual rendering of the points where the user has been looking at.

Discussion of experimental results

From the accuracy tests an RMS error of 54, 34 pixels for the X coordinate and 56, 56 pixels for the Y coordinate was found. This error is used to provide a margin around the user interface elements, so that there is no overlap in their bounding boxes. This then simplifies association of the user's gaze to a certain feature.

The combined heatmap of the experiments is plotted in Figure 2. The figure shows clearly that the main focus is in the centre of the screen with some attention going towards the distance indicator and the map. In Table 1 the percentages of which element the user looked at during the experiments is provided for each experiment. The experiment suggests that when ablation targets are separated further the trainee resorted more to the use of the map. When targets are closer to each other the user may have found it more convenient to quickly scan around instead of moving the gaze up to locate the map. From talking with the user, it was found that the distance indicator is especially used when closing in to a correct lasering distance. When compared to each other, the map may be used more, as navigation from one point to another point takes more time than keeping a laser at a desired distance.

Table 1. Summary of experimental results; in both tasks the main focus lies at the screen centre, while other elements draw attention based on the design of the task.

	Lines 1	Lines 2	Lines 3	Seq 1	Seq 2
Overview Map	2.361%	6.87%	14.038%	15.038%	0%
Distance Indicator	3.127%	2.021%	3.472%	2.506%	1.657%
Centre of Screen	94.512%	91.109%	82.483%	82.456%	98.343%

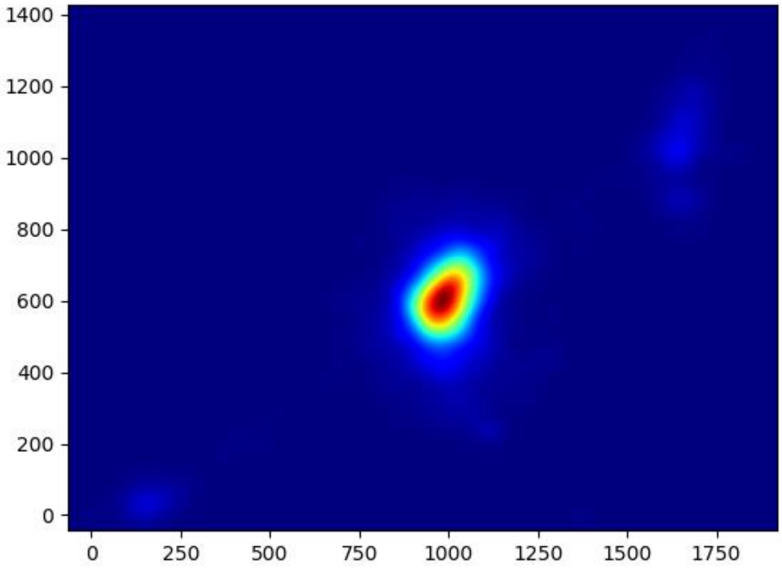

Figure 2. Combined Heatmap of all experiments; centre of the screen has main focus; distance indication on the bottom left and map with overview on the top right both gained attention; x and y axis in pixels.

Conclusion

This work aims to validate the use of assistive AR technologies for TTTS surgery. Two assistive technologies are investigated via a virtual simulator: a distance indicator and an overview map of the placenta. Both features were validated using an eye tracker. Firstly, it can be concluded that the accuracy of the tracker is sufficient to be able to distinguish what element of the screen the user is looking at. Secondly, from the data, it can be seen that the proposed assistive technologies have been used. The time spent looking at these elements is relatively low so it appears that at such level it is not distracting from the main task which is still happens in the centre of the screen. To conclude it appears that there is a good potential for both assistive technologies under test. The map could help navigation between points as well as reducing the mental load for the surgeon who does not need to memorise anymore all the details of the surgery. When unsure, the distance indicator may offer more certainty as to what depth has been reached and how far this is from an ideal laser distance. To confirm this potential more extensive experiments are needed however with more participants including expert surgeons. A follow-up study would link also the outcome metrics to the information obtained from the gaze as it is still to be confirmed that the extra information – even if used by the operator – effectively results in a better surgical outcome which is of course the ultimate goal.

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Review Paper: Commercial Haptic Gloves

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Introduction

Of all VR interaction devices, the haptic glove is at the same time the most desperately asked for and the most complex to develop. Indeed, each human being not only has a unique hand size and shape, but also a pair of hands which are not identical and not even symmetric. In addition, the hand is one of the most sensible parts of the body. It is able to perceive fine details at very large frequencies, but may also develop and perceive large forces (Lederman et al., 1988). As a consequence, in order to be effective a haptic glove has to be adaptable to its user. It needs to be light-weight and compact, yet deliver large amounts of power with a very low latency.

For many years, the only mature wearable force-feedback devices for the hand have been the CyberGrasp™ of Immersion Corp (now CyberGlove Systems) (www.cyberglovesystems.com; Turner et al., 1998) and the Master II of Rutgers University (Bouzit et al., 2002). Neither of them enjoyed a great commercial success. There have been many research projects proposing the use of classical DC motors, artificial muscles, shape memory alloys or dielectric elastomers. An exhaustive review of the developments in academia has been pub-lished recently by Pacchierotti et al. in 2017. The purpose of this paper is to focus on commercial devices and to describe the current status of these systems.

User requirements and constraints

The sense of touch is extremely complex, and cannot be addressed by a unique actuation principle. For this reason it is common to distinguish between “tactile” and “kinesthetic” touch. Tactile feedback devices provide input to the user’s skin. They try to recreate the sensation of a shape, a texture or in some situations even of thermal properties of a virtual object. Kinesthetic feedback devices apply forces to the skeleton of the user. They create an impression of movement and/or resistance through the muscles. In real life, both feedback types are present when touching an object. In order to experience tactile feedback only, one may try to touch an object placed on a slippery surface, so that it offers no resistance. Similarly, one could isolate kinesthetic perception by touching an object while wearing very thick gloves effectively filtering out the tactile component.

The main user requirements for a haptic glove are as follows: the glove should provide both tactile and kinesthetic feedback, it should be wearable (i.e. not heavy) and should not impede the natural movement of the fingers. Because the need to produce in large numbers to reach an acceptable market price, gloves either need to fit an arbitrary size and form of the hand or should be easily adaptable. Latter constraint is usually addressed by offering a selection of sizes within a certain working range. This approach is to some extent similar when purchasing rubber gloves for the household. However, it is not as simple as that as it becomes tedious when actuators need to be placed very precisely relative to the user's anatomy.

Classification of haptic gloves

To simplify the analysis, the following classification of haptic gloves is adhered to in this work:

- traditional gloves,
- thimbles and
- exoskeletons.

Although the different classes all share the same objectives and constraints, the three categories follow very different technical approaches to meet with the said objectives and constraints. In the following the three categories are explained and examples of representative commercial products are analyzed in greater detail.

Under the name "traditional glove" a garment made of some sort of flexible fabric, which fits the shape of the hand and lets the fingers move individually, is understood. The sensors to measure the flexion of the fingers and the actuators to apply a feedback on the skin or skeleton are either sewn within the fabric or fixed on the outside of these gloves.

The designers of this type of haptic glove face several challenges. First, the sensors and actuators must be small enough to fit inside the fabric or to allow placement very close to the fingers. Second, the whole equipment (including wiring) needs to be very flexible, otherwise the user will feel restricted in his/her movement. Third and last, the glove must be able to sustain large deformations, including stretching that appears when fitting in and out. The glove should undergo these deformations repeatedly without damage to its structure or affecting its functionality.

Traditional Gloves

The Spanish company Neurodigital Technologies has announced the development of such a haptic glove, in two versions, the Gloveone™ and the AvatarVR™ (www.neurodigital.es/gloveone). Both products provide interaction with the 5 fingers, with 10 vibrotactile actuators placed as follows: one is located under each fingertip, three under the palm, and two on the back of the hand. The type of actuator used is unclear. The hand pose is measured by an IMU in both products, the Gloveone uses flex sensors to measure the fingers position whereas the AvatarVR uses IMUs for each finger. As of March 2018, it is possible to order the products on the company website, but according to discussions on the forums, there are some problems with delivery.

The company Senso, based in the USA, has been working since 2015 on the "Senso Glove™" (https://senso.me; Giusto et al., 2016). It provides interaction with 5 fingers, with one vibration motor under the last phalange of each finger. The measurement of finger and hand movements is based on inertial sensors. This makes the device cheap and easy to calibrate and ensures a high refresh rate, but at the cost of precision. Integrated pressure sensors measure the grip pressure. The Senso Glove comes in S, M, ML, L and XL size for men and S, M, L for women. As of March 2018, the second version of the product is available for software developers. The customer version is said to be 6 months late with respect to the company's website information.

Very recently, the German start-up company Cynteract has started working on a new glove concept for rehabilitation (www.cynteract.de). They are using a standard glove made of cloth, to which they add wires attached to servomotors, capable of exerting a force along the whole finger, in either opening or closing direction. The actuators and electronics are mounted on the forearm. The electronics of the glove measure not only the bending of the fingers but also the orientation in space, so that it is usable without an additional tracking system. The first prototypes are undergoing early clinical trials.

The Maestro glove from ContactCi (Cincinatti, US; https://contactci.co/) follows a similar principle. Five exotendons are connected to the same amount of servomotors assembled in a package that is mounted on the operator's forearm. The exotendons are routed along the upper body of the hand towards the different fingers. Embedded in a traditional glove they restrict the finger motions when fingers touch an object in the virtual reality environment. Five fingertip pads are responsible for vibration cues. 5 Flex sensors and the exotendon positions are being measured in the Maestro. Contact Ci is accepting applications for early beta testing, but does not give an indication when the Maestro will be released to the broader public.

Thimbles

By "thimble" a configuration with an actuator attached to a fingertip is meant. If it is possible to combine several thimbles in order to provide feedback on several fingers at the same time. In such way a function similar to that of a haptic glove can emerge.

The challenge in designing thimbles lies in the need to integrate sensors, actuators, a power source and a wireless transmission within a very light and compact device. In addition, the thimble needs to fit on fingers of different sizes without squeezing them painfully while avoiding the risk for slipping.

The device VRtouch™ of the French company GoTouchVR is a simple thimble with only one electromagnetic actuator, which applies pressure to the finger-tip (www.gotouchvr.com). By means of a magnetic clip the thimble can be easily attached to the finger. Multi-finger touch is possible by mounting multiple devices on different fingers (3 per hand maximum). As with all thimble solutions collisions between modules prevent gestures where fingers are too near. The VRtouch™ supports Leap Motion and some other third party tracking systems to track the hand and finger. The product is available since November 2017 for software developers.

The company Tactai, based in the USA, also proposes a thimble called "Tactai Touch™" (www.tactai.com). Based on 15 years of academic research, the device is able to render sensations of pressure as well as texture and contact (Pacchierotti et al., 2017). A single thimble is said to weigh approximately 29 grams (Pacchierotti et al., 2017). Again, software developers can pur-chase a kit, but Tactai has not yet announced a final release date for the consumer market.

Exoskeletons

An exoskeleton is an articulated structure which the user wears over his/her hand, and which transmits forces to the fingers. Because of the need to adapt to a variety of hand sizes and shapes, designers do not usually adopt the same kinematics as the fingers because it would require for each user a very precise adjustment of the segment lengths. Instead, the structure runs in parallel to the fingers on the outside of the hand. A number of intermediate linkages attach the exoskeleton then to the different phalanges of the hand.

The CyberGrasp™ is the most famous and the forerunner of all commercial exoskeletons (www.cyberglovesystems.con; Turner et al., 1998). The role of the very complex mechanical structure is to convey the force of a pulling cable to the fingertip without constraining the other joints. The movement of the fingers is not measured by the exoskeleton, but by a dataglove (CyberGlove) worn under it by the user. The maximum force (12 N) is large enough to stop completely the movement of a finger. However, the effect of having one's fingertips pulled backwards while nothing is happening on the phalanges and palm is very strange and not so convincing. Nevertheless, the company has been selling the device successfully for more than 20 years. Because of the high price and the very small number of available applications, the sales number have been low (about 2-5 pieces per year). Still, it is a serious achievement for a device that has been so much ahead of its time.

In the new generation of exoskeletons, the Dexmo™ by Dexta Robotics (China) has been highly anticipated, with its impressive design resembling a large claw (www.dextarobotics.com). The first prototypes used mechanical brakes to simulate the resistance of virtual objects (Gu et al., 2016), but the final version integrates servomotors for a variable force-feedback. The exoskeleton measures finger flexion and abduction, plus one rotation for the thumb. The force-feedback is limited to one degree-of-freedom per finger, with a maximum force of 0.3 Nm. The start-up Dexta Robotics has had a hectic course, after cancelling a first crowd-funding campaign. As of March 2018, only development kits are available, and highly priced (Table 1).

The US-based company HaptX Inc. has a very different and challenging approach. The design of the HaptX Glove™ resembles an armored glove, and the actuation principle is pneumatic (https://haptx.com). The complete device features a smart silicon-based textile and integrated air channels that delivers high-resolution, high-displacement tactile feedback combined with a biomimetic exoskeleton for resistive force feedback. Magnetic sensors capture the finger movements with sub-millimeter motion tracking accuracy. The HaptX Glove includes more than 100 tactile actuators and delivers up to 22 N of force feedback. HaptX Gloves are focused on VR training and simulation applications for industrial users. Development Kit versions of the gloves will ship to select enterprise customers later this year.

The VRgluv™ is another exoskeleton coming from the USA. Also this glove looks like an armored glove (https://vrgluv.com). The company announces 20N of force-feedback, high-frequency movement in 12 degrees-of-freedom and pressure measurement. Although the product developers are not releasing any technical details, apparently the exoskeleton is actuated by DC motors pulling cables. After a successful crowdfunding campaign closed in May 2017, the VRgluv team have not yet announced when production will be started.

The Dutch company Sense Glove is also busy developing an exoskeleton (www.senseglove.com). The first version used mechanical brakes and was entirely 3D-printed. This enabled the company to enter the market very quickly. The device applies unidirectional force-feedback on the finger flexion (in the direction of grasping), using one servomotor per finger pulling on a string, and can also apply vibrations. The maximum force is 7 N. A batch of development kits have been delivered in 2017, and the first small series production is announced for Summer 2018.

Under the name EXOS, the Japanese company exiii is developing several devices, for example a claw-like device with one single degree-of-freedom (http://exiii.jp). Of higher interest for this paper, the company is also developing an exoskeleton for the hand, called "EXOS Glove", together with the Japanese company Taisei Corp. The targeted application is remote control, in combination with a robotic hand. The haptic glove is equipped with 5 servo-motors, but other than that, no technical details are being published. No announcement has been made on a possible market release date.

Finally, the French company Haption has demonstrated a prototype called the HGlove at several academic conferences and trade exhibitions (Figure 1; www.haption.com). Contrary to the other products, it provides interaction only for the thumb, index and middle finger. The device is attached to the hand via two straps with hook and loop fasteners around the palm and thumb. Two tiny DC motors apply a force on the fingertip through a two-bar mechanism with a reduction based on one gear and one small capstan. Consequently, the interaction works not only on the flexion/extension, but also on the rotation around the first phalange. The abduction is measured but no force-feedback is available on that movement. The maximum peak force is 12 N, and the maximum sustainable force is 5 N. It is possible to attach the HGlove to a force-feedback device such as the Virtuose 6D, which applies a force to the hand via a rigid fixation on the back plate of the exoskeleton. The HGlove is available for sale as single piece manufacturing. Haption does not plan production in series at this date.

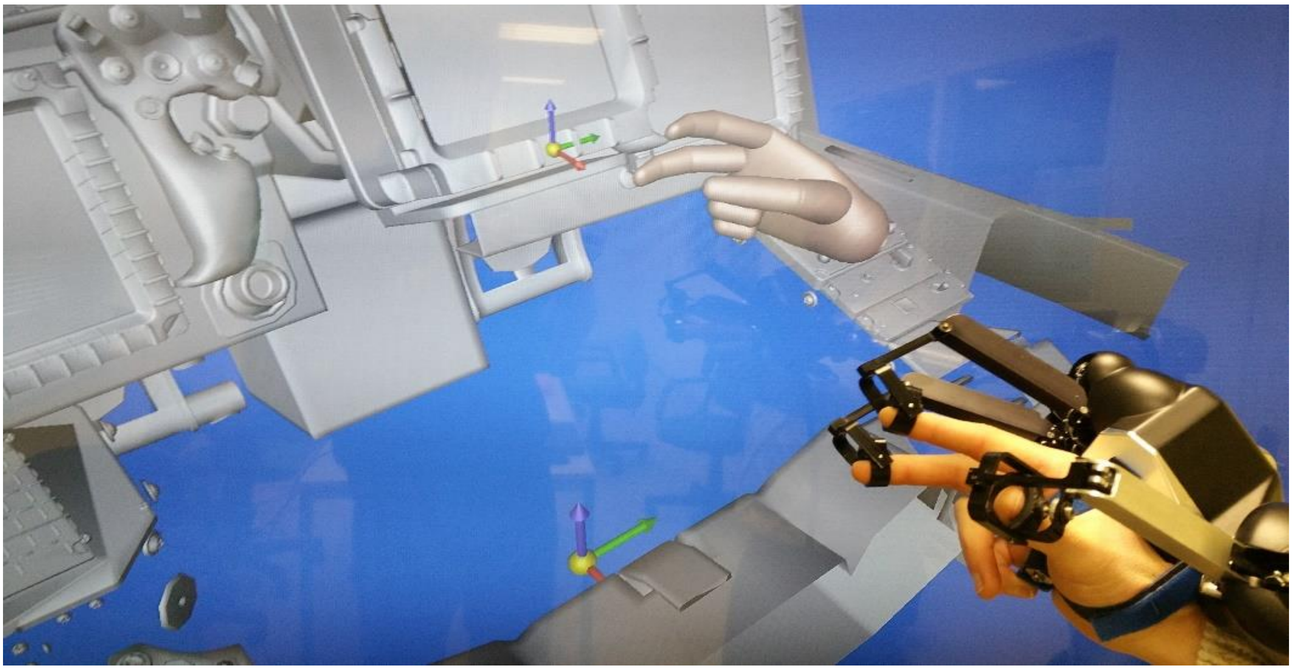

Figure 1. Prototype of the HGlove.

Like most exoskeletons, one major difficulty in the implementation of the HGlove in Virtual Reality comes from the mechanical structure: because of the need to adapt to any hand size and shape, it needs a much larger workspace than the actual fingers of any particular person. Not only has Haption designed the structure with only two joints where the human finger has three. The offset be-tween the joints and the phalanges are large so that there is no correspondence between the joint angles measured by the motor encoders and the finger pose. One solution could be to have the user wear a dataglove, thus measuring the finger pose directly. The solution proposed by Haption is to describe a model of the hand and use inverted kinematics in order to calculate the finger pose. By measuring a few standard hand poses at the start, the system calibrates the model to the actual size and form of the user’s hand within a few seconds.

Conclusion

As shown in Table 1, the actuation principles chosen by the developers of haptic gloves for commercial products tend to narrow down to a very limited number of solutions. Except for HaptX who relies on a smart textile with embedded air channels, which as a consequence implies that it cannot be made wireless, all other commercial systems are using traditional electromagnetic motors. This stands in contrast to the plethora of drive mechanisms that have been and are being explored by research teams worldwide (Pacchierotti et al., 2017). Nevertheless, it appears that even with such proven technology, the designers experience considerable challenges to deliver the promised products in due time.

Table 1. Overview of commercial haptic gloves.

Device	Type	Nb fingers	Wireless	Actuator	Force-feedback	Tactile feedback	Hand tracking	Active DoFs	Weight (g)	Published price
Gloveone	Glove	5	yes	Electromagnetic	no	yes	yes	10	na	499 €
AvatarVR	Glove	5	yes	Electromagnetic	no	yes	yes	10	na	1100 €
Senso Glove	Glove	5	yes	Electromagnetic	no	yes	yes	5	na	599 $[1,2]
Cynteract	Glove	5	yes	Electromagnetic	yes	no	yes	5	na	Na
Maestro	Glove	5	yes	Electromagnetic	yes	yes	yes	5	590	na
GoTouchVR	Thimble	1	yes	Electromagnetic	no	yes	no	1	20	na
Tactai Touch	Thimble	1	yes	na	no	yes	no	1	29	na
CyberGrasp	Exosk.	5	no	Electromagnetic	yes	no	no	5	450	50000 $[3]
Dexmo	Exosk.	5	yes	Electromagnetic	yes	no	no	5	320	12000 $[1]
HaptX	Exosk.	5	no	Pneumatic	yes	yes	yes	na	na	Na
VRgluv	Exosk.	5	yes	Electromagnetic	yes	no	no	5	na	579 $
Sense Glove DK1	Exosk.	5	yes	Electromagnetic (brakes)	no	no	no	5	300	999 €[1,2]
EXOS Glove	Exosk.	5	no	Electromagnetic	yes	no	no	5	na	na
HGlove	Exosk.	3	no	DC motor	yes	no	no	9	750	30000 €[3]

[1] Development Kit (DK), [2] Two pieces (left and right), [3] Single piece manufacturing

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Title	**The Industrial Track of EuroVR 2018** Proceedings of the 15th Annual EuroVR Conference
Author(s)	Kaj Helin, Matthieu Poyade, Mirelle D'Cruz & Richard Eastgate (eds.)
Abstract	**EuroVR 2018: London** The focus of EuroVR 2018 is to present novel Virtual Reality (VR) up-to Mixed Reality (MR) technologies, including software systems, display technology, interaction devices, and applications. Besides papers on novel results, industry-oriented presentations (automotive, medical, etc.), the EuroVR conference series create a unique opportunity for participants to network, discuss, and share the latest innovations around commercial and research applications. As the previous years, we welcome industrial and academic exhibitors, as well as sponsors, all within the same exhibition area, to connect with our community. Our major priority is to provide authors the opportunity to spread with an excellence label their innovative works within the wide community of end-users, from large industry up to SMEs.
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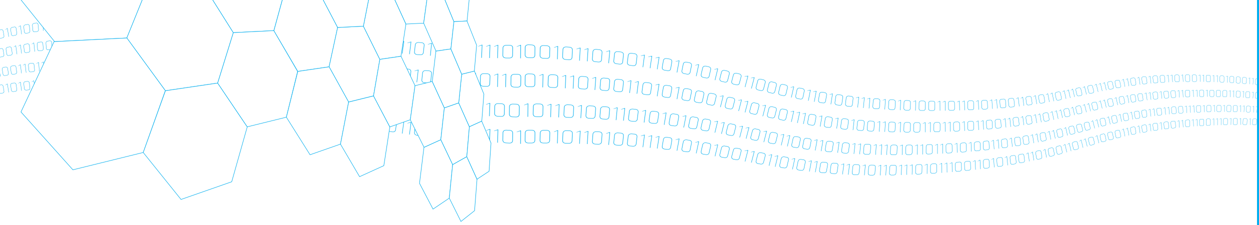

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