PROCESS DRIVEN FRAMEWORK FOR AUGMENTED REALITY IN A MANUFACTURING ENVIRONMENT

Krzysztof J. Rechowicz [(a)], Hector Garcia [(b)]

[(a),(b)]Virginia Modeling, Analysis, and Simulation Center, Old Dominion University, Suffolk, VA, USA

[(a)] krechowi@odu.edu, [(b)] hgarcia@odu.edu

ABSTRACT

In many domains where VR has proven its value, augmented reality (AR) starts getting recognition as a viable alternative to its more mature predecessor. Unfortunately, it has been suffering from similar challenges that VR needed to overcome. Some application domains, e.g. manufacturing, pose additional barriers preventing AR for widespread. So far in manufacturing, AR applications have been built with a specific task in mind and were mostly prototypes. In this paper, we focus on an AR application for process control with an emphasis on a generic process structure. This approach would allow to reuse the AR application in a range of processes which could be easily defined by a limited number of parameters. To test this approach, we developed an AR application using off-the-shelf components and applied it to a machining process in an actual manufacturing center. We used up to thirteen parameters to define each step of the process and provide input to the algorithm driving the AR application. We established that the experience of developing a process-centric AR tool was feasible and allowed the user to leverage just-in-time information available through the AR display.

Keywords: augmented reality, process control, process monitoring, advanced manufacturing

1. INTRODUCTION

Many domains, including manufacturing, have benefited from the introduction of virtual reality (VR). Before this could happen, researchers and industry had spent decades on maturing the technology to the point where it can now be successfully used, especially in training and education. For many years, however, it was common to oversell VR to the end user despite its very little value which had a significant impact on technology acceptance. Focusing on the technology limitations, rather than on how it could add value was characteristic for many industries. Fortunately in recent years, we have been observing a paradigm shift in the approach to this technology leading to better recognition of its potential and new applications. Unfortunately, augmented reality (AR) has been suffering from similar challenges that VR had to overcome. Promotional materials and concept videos are setting user's expectations too high. They present the technology as being capable of accommodating a variety of specialized scenarios with effortless customization spanning across various domains which in reality has not been achieved yet.

Similarly, computer-based augmentation for manufacturing applications will not follow the one-size-fits-all principle in the near future. First, manufacturing is a broad domain encompassing a large number of processes with a varying range of human activity. Second, an AR system has to be a part of the cyber-physical infrastructure of an enterprise. Since cyber-physical systems (CPS) are themselves in the initial stage of development, there is a need of defining guidelines for their implementation in the industry, taking into account the principles of Industry 4.0 (Kagermann, Helbig et al. 2013). Industry 4.0 assumes CPS integration across the whole manufacturing operation, i.e. logistics, services, and production which requires a unified system framework, which is part of ongoing research efforts (Lee, Bagheri et al. 2015). Eventually, AR systems will have to be abundantly integrated with a unified framework and be a worker's window to CPS (Kagermann, Helbig et al. 2013).

Industry 4.0 recognizes a human operator as the most flexible asset in the manufacturing environment requiring a high level of adaptiveness to ever increasing complexity of the production settings (Schmitt, Meixner et al. 2013). Under the Augmented Operator principle of the fourth industrial revolution, an operator needs to be equipped with tools which allow for monitoring of manufacturing processes from almost anywhere and, if necessary, provide guidance through. Mobile user-centered technologies with intuitive user interface are currently able to potentially fulfill this task since they already provide support when the user tackles a wide selection of problems (Gorecky, Schmitt et al. 2014). However, currently available technologies, i.e. smart-glasses and watches, smartphones, and tablets, in their majority are not designed to meet the requirements of the industrial environment.

Academia alone cannot address these issues and close collaboration with the industry is needed. In recent years, we could observe academia-industry initiatives, started to accomplish a higher level of efficiency through the introduction and adoption of industry-grade

AR, e.g., the Augmented Reality for Enterprise Alliance (thearea.org).
The research approach in this paper focuses on the development of a framework for the integration of AR for industrial process control with the aim to guide the user through a process and visualize relevant information in real-time. To test the framework, we applied it to a machining process executed at the Commonwealth Center for Advanced Manufacturing (CCAM) – an applied research center bringing universities and manufacturing industry together.

2. AUGMENTED REALITY

AR is an enhanced version of reality where digital information is overlaid over a direct or indirect view of a physical environment. Although AR is typically associated with vision, it can also refer to other senses, like audio (Mavor and Durlach 1994) and tactile feedback (Wellner 1993). In the case of visual augmentation, one can argue that only overlaying information over a direct view constitutes real AR. For some applications, however, an indirect view AR may be more beneficial to the end user than a direct. Therefore, we consider both types of AR in this paper.
An AR system typically consists of hardware, i.e. display, input devices, sensors, etc., and software and algorithms, including image, object recognition and registration.
The augmentation process is device and application dependent. Figure 1 shows its generalized version for manufacturing applications. Internal sensors gather information about the current state of the AR device and its surrounding, including visual input.

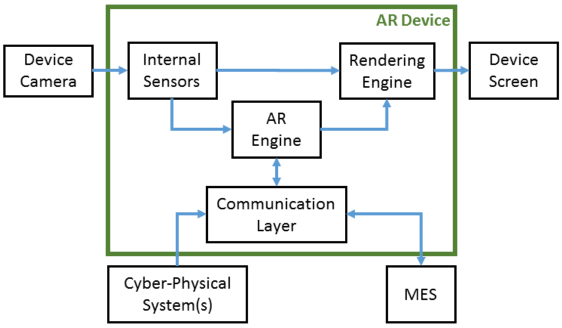

Figure 1: Augmentation Process

The heart of the system is an AR engine responsible for object recognition and registration by the means of computer vision. An AR engine is also typically used to develop an AR experience.
A communication layer is a critical component of an industry-grade AR system enabling two-way data exchange with the CPS, enterprise resource planning (ERP), and/or manufacturing execution system (MES). Connectivity with CPS includes machines and sensors, ideally through MTConnect or Open Platform Communications Unified Architecture (OPC UA). Communication with ERP/MES can be more challenging since those systems tend to be enclosed and an AR system needs to be tailored to accommodate their specificity. Some information may need to be updated at a higher frequency, e.g. machine state, whereas certain information, e.g. CAD model, is not required to be updated at such high frequencies.
The AR engine generates digital content which is then rendered over a video feed or on a semi-transparent surface, depending on the form factor.

2.1. AR Form Factor Classification

There are currently several AR form factors available on the market: head-mounted displays (HMDs), projection-based, and handheld. HMD is a display device worn on the head or as part of protective gear, which has a small optic display in front of one (monocular) or each eye (binocular). HMDs for AR applications come in three forms: Video see-through, where users cannot directly see the physical world, and instead see a live video which is sampled by a camera; A miniaturized video see-through, which allows users to directly see the physical world via a live video sampled by a camera and presented on a miniaturized display; and an optical see-through, which possesses the capability of reflecting projected images on the real world environments as well as allowing the user to see through the display.
A hands-free display is one of the most notable advantages of HMDs. However, interaction with the AR experience may require manual input from the user. Video see-through HMDs provide higher level of immersion than the other two types and controls the user's entire field-of-view (FOV). However, wearing video see-through HMDs may affect a user's visual acuity and cause simulation sickness. This type of HMD may also be uncomfortable for the user due to the hardware's weight and bulkiness. On the contrary, miniaturized video and optical see-through HMDs are typically lightweight and do not cause simulation sickness. However, miniaturized video see-through devices are characterized by lower FOV and require the user to change focus. Limited computational power of this form factor cannot be neglected since this implementation would require to display 3D content and a smooth user-device interaction via a haptic device. Miniaturized displays have also lower resolution when compared to other devices. Optical see-through HMDs, on the other hand, suffer from narrow FOV which requires the user to be looking almost directly at the area of interest. Due to the hardware design, the overlay image is never fully opaque which allows to see the environment behind the computer-generated object (Azuma 1997).
Another AR form factor is projection-based where a projector is used to project information on real objects. This form factor may be beneficial when the environment is large. Similarly to HMDs, it is a hands-free display and the user does not need to switch focus between the image plane and the real environment with optionally multiple users. This form factor, however, requires an environment with low light-intensity and is

not highly mobile. It also requires a physical object for image projection so it may be hard to generate virtual objects midair (Cebulla 2013).
The last form factor, handheld, is very popular since it includes smartphones and tablets where the live video is sampled by the camera. Handheld devices are typically affordable, ubiquitous, do not restrict user's FOV, have multi-sensor and network capabilities, and are rich in on-board computational resources. Unfortunately, such a device needs to be held when in use which limits the user's manipulation capabilities for the task at hand. Special attention to the security of such devices needs to be considered when implementing their use in industrial settings in order to minimize any compromise of the data being used while operating such devices.

2.2. Safety

Safety is a major concern in the manufacturing industry and the magnitude of general industry safety standards can be overwhelming. Although the use of AR is expected to contribute to an increase in safety (McCutcheon, Pethick et al. 2016), it could also be a source of safety violations. Furthermore, AR equipment needs to meet industry safety standards and requirements.
To better illustrate the case, in the US, many organizations require their workers to wear protective eyewear which typically has to be in compliance with industry standards and the Occupational Safety and Health Administration (OSHA) regulations. Currently, the majority of HMDs, especially see-through, are not certified for the shop floor.
View management is another aspect that can negatively influence a worker's safety. Industrial environments are typically dynamic and require situational awareness. It will become even more critical with widespread of autonomous robots and machines. Computer generated content in AR, e.g. 3D models and annotations, can potentially overwhelm a user's view due to the amount of information AR systems can provide. Some researchers have discussed the need of actively managing a user's interface and digital content to avoid confusion and eliminate any safety issues.
Höllerer *et al*. (Höllerer, Feiner et al. 2001) proposed three user interface design techniques, i.e. information filtering, user interface component design, and view management, to provide a more intuitive interaction and better organized digital content. For information filtering, the authors leveraged the concept of a situated user interface that depends on the user's location, physical context, tasks, and objectives, which are also the same three key elements in AR applications for manufacturing.
Motivated by the need to improve readability and intelligibility of the annotations, Makita *et al.* (Makita, Kanbara et al. 2009) developed a system which obtains positions and shapes of target objects, and penalize location of annotations that overlap and/or occlude the target. Not without importance was the distance between the annotation and the object in the current and sequential frames. The system was supplemented, besides a video camera, by an infrared camera to detect people in the scene and calculate how much the region in a frame was occupied by the user. The functionality proposed by the authors would decrease the risk of annotations blocking a user's view in busy environments. However, this approach focuses only on people, whereas an AR system deployed in industrial settings would need to be able to detect autonomous machines and robots.
Tsai (Tsai 2013) recognized a similar problem in AR applications to transportation and proposed a safety view management mechanism to display information on AR devices in a safer manner. In this approach, a region on a device screen where labels or annotations can be displayed without overlapping moving objects is continuously calculated increasing the user's safety.
The aforementioned safety issues are mostly applicable to optical and video see-through HMDs. A video see-through HMD may introduce an additional set of safety problems. Due to the typical characteristics of this form factor, the display takes up virtually the entire user's field-of-view (FOV) with the casing closely adhering to user's face. In this way, a user's peripheral vision is significantly limited, hence he or she may not have full situational awareness.
Another safety concern associated with this form factor is the complete loss of vision if the device runs out of power or malfunctions. The user may not always be able to react immediately, e.g. while performing a manual task.
Misalignment between the camera(s) (typically one camera per eye) and the user's perspective (Kanbara, Okuma et al. 2000, Colgan 2015, Samini and Palmerius 2015), in the case of device-perspective rendering (DPR), can also be a causative factor behind safety issues. When an AR application is being developed, there are typically three camera types, i.e. virtual, physical, and biological, that need to be considered (Colgan 2015). Although placing the cameras at the same height as user's eyes, i.e. biological cameras, is not currently problematic, separation between two cameras of each type, except virtual cameras, cannot be freely changed. This discrepancy can lead to a user's incorrect conviction concerning his or her position in the physical world. Therefore, video see-through form factors should not currently be used in industrial settings.
User's safety while using AR in industrial settings is an undisputable concern. However, safety of CPS should also be considered by the stakeholders. We can expect that AR devices used in the manufacturing domain will be connected to CPS under the Internet of Things (IoT) paradigm. However, there is no consensus how to best implement security in IoT at any IT level (River 2015). Daniels (Daniels 2014) discussed cybersecurity implications of AR applications from the perspective of an end user, i.e. geo-location services, always-on data input, and social networking and media. However, these implications have been known since the introduction of

modern mobile devices. They are also inherited by AR especially as far as the general audience is concerned. Since AR in manufacturing is information driven, it would be more appropriate to look at factors that could lead to data compromise.

3. METHODS & MATERIALS

An AR system typically consists of a hardware and a software component. In this section, we focus on the devices used and the AR application we developed to accommodate a manufacturing process.

3.1. Hardware

To better understand how various form factors fit modern manufacturing environment, we chose a Nexus 7 (ver. 2013) and an Epson Moverio BT-200, both powered by Android, which represent a handheld and HMD optical see-through form factors, respectively. The camera and user input method are one of the most important factors influencing the performance of AR applications. The tablet camera has 1920x1200 resolution, whereas the glasses is limited to 640x480. In the tablet's case, the user interacts with the system mainly through the touchscreen, whereas the glasses are equipped with a separate touchpad. Additional input is possible through built-in sensors and microphone. The glasses are also characterized by a limiting 23º FOV.

3.2. Software

The AR application was developed in Unity (Unity Technologies, San Francisco, CA, USA) – a cross-platform game engine, supplemented by Vuforia (PTC, Needham, MA, USA) – an AR Software Development Kit (SDK). The application consisted of four main components: a rule-based process control framework, communication, pattern recognition, and GUI.

In the application, each manufacturing process is defined by a set of steps that need to be executed in a particular order. Each step is defined by up to thirteen step parameters depending on its type and can be triggered by either manual input, recognized feature, and readings from a machine. Some process steps may consist of a sub-process which does not have any major implications on the algorithm other than for time reporting purposes. The parameters are as follows (optional and dependent parameters marked with an asterisk):

- Step name (string)
- Subprocess (integer)
- Displayed text (string)
- Object to display (2D/3D object)*
- Manual input required (y/n)
- Sensory input required (y/n)
- Sensory input name (string)
- Parameter type (string/number)*
- Triggering values (string/number)*
- Operation type (less than, greater than, equal)*
- Name of the object to track (string)*
- Text over the indicator (string)*
- Indicator position (vector)*
- Next step (integer)

To reduce the number of parameters, some of them can inform the processing algorithm by their mere presence how to proceed. For instance, if the sub-process parameter has any value, it indicates that the entry is part of the process step.

In addition to the parameters, the data structure stores the step completion time which can be uploaded to MES for further manufacturing process analysis.

Since some steps rely on object recognition, we used Vuforia's capability to recognize and track planar images, also known as image targets. A set of images corresponding to equipment and other significant locations on the shop-floor was taken and converted to image targets. The conversion process extracts salient features that are later tracked within the camera's frames. The target will be tracked as long as the target is at least partially visible and tracking is lost once not enough target features are available. However, Vuforia allows the application to continuously learn its environment by detecting other features beyond those in the image target, also known as extended tracking. However, not every image can serve as a stable target. Each target is rated from 0 to 5 based on its quality. To achieve a high rating, images should be rich in detail, have good contrast, and exclude repetitive patterns, because the system looks for sharp, spiked, and chiseled details. **Error! Reference source not found.** shows examples of high (left) and poor (right) target quality with identified salient features.

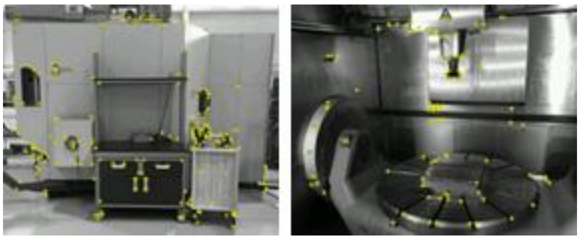

Figure 2: Target Quality of AR Image Targets: High (left) and Poor (right)

To better understand limitations of image tracking, we performed simple tests using the aforementioned devices. In the first test, we gradually covered an image target of high quality with uniformly distributed features and measured the amount of the target covered when tracking was lost. In the second test, we gradually uncovered the image target and measured the amount of the target uncovered when tracking was established. We also measured the angular position of the camera with respect to the target when tracking was established and lost.

The tests indicated that tracking was lost when 80% (tablet) and 70% (glasses) of the image target was covered, respectively. The image target was detected when between 20% (tablet) and 45% of the image target was uncovered, respectively (**Error! Reference source not found.**). To detect an image target, the camera needed to be approximately perpendicular with ±15º deviation.

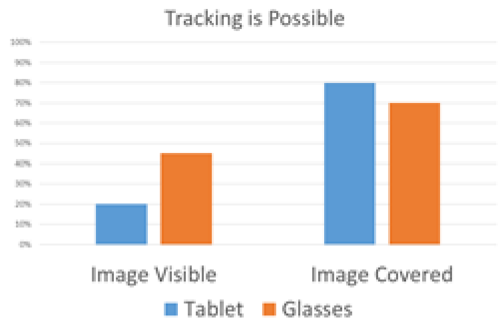

Figure 3: Range of Tracking Ability Between Tablet and Glasses

A simple 3D model of the shop-floor can be used to place the image targets matching the locations of interest around the facility. For items that are mobile, like shop carts or parts, object targets can be created by scanning physical objects. This step allows for registration of the physical and virtual environment. Unless new equipment is added, this task has to be performed only once. A 3D model is used for better user's spatial perception and the whole process can be executed at run-time by providing spatial relative correspondence between image targets. Image target themselves can be stored in a remote location which allow for the ability to edit and substitute image targets without any action from the user.
Since AR applications typically run on mobile devices with limited computing power and storage, communication with databases and sources of data is an important feature. We leverage Extensible Markup Language (XML) for data exchange since it is both human- and machine-readable, readers and writers are easy to implement, and used by MTConnect. We set up a simple web server *in lieu* of MES to store process information and to which real-time machine data was sent.
When the application starts running, the user is prompted to choose an outstanding order. Each order has an associated list of steps that needs to be executed by the worker. Then, the processing algorithm (**Error! Reference source not found.**) reads in the first step in the process. Based on the process step parameters, the type of the step is identified and the algorithm utilizes related parameters to run the scenario. To avoid false step completion reporting, steps utilizing tracking require the user to provide confirmation.

3.3. Case Study

To test whether the application and chosen form factors, and, to be more precise, the chosen hardware can accommodate work in a manufacturing environment, we applied the proposed tools to a machining process at CCAM. The process was augmented to accommodate the specificity of CCAM members' operations. The process was developed with assistance of an experience machinist and consisted of the following steps:

1. Choose order (manual)
2. Localize raw part pickup area (tracking)
3. Localize raw material (tracking)
4. Localize assigned machine (tracking)
5. Fixture part (manual)
6. Choose program file (manual)
7. Start machining (sensory)
8. Machine (sensory)
9. Remove from fixture (manual)
10. Inspect part (manual)
11. Metrology lab (tracking)
12. Generate report (manual)

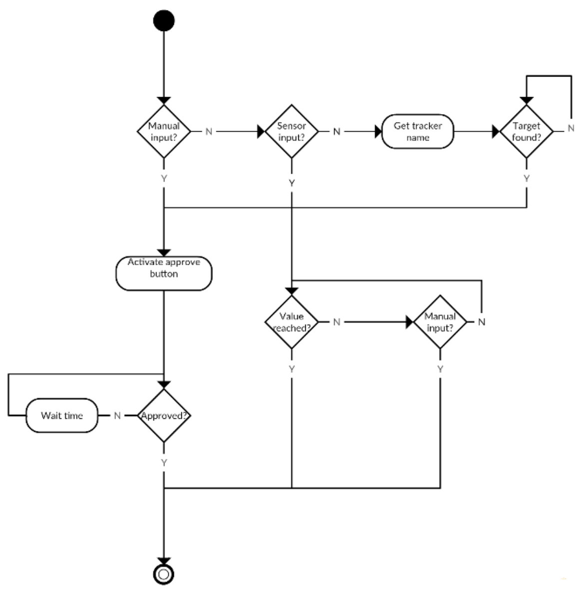

Figure 4: AR Application Algorithm

Process step #8 consists of sub-steps triggered by M01 program stops, included in the CNC program generated to mill a pocket in a cube. Two M01 commands are related to tool wear measurements and one in between requires the machinist to adjust the fixture. All stops were introduced to the program for testing purposes but the user is required to take action based on the system's recommendation and to resume program execution. Additionally, process step #10 consists of three sub-steps requiring the machinist to measure indicated features in the finished part.
A section of the shop-floor was modeled using simple geometric solids indicating location and bounding box of equipment and shop-floor important features (**Error! Reference source not found.**). Respective image targets were created by taking photographs of the equipment. All image targets had the augmentation rating of four and up. The image targets were placed at their respective locations. It is important to indicate that neither the image targets nor the shop-floor model is visible to the user while using the application.
For the purpose of this project, we set up a remote server to store all process-related information including live machining data obtained through an OPC server connected to a Hermle c42 – a high-performance 5-axis CNC machining center.

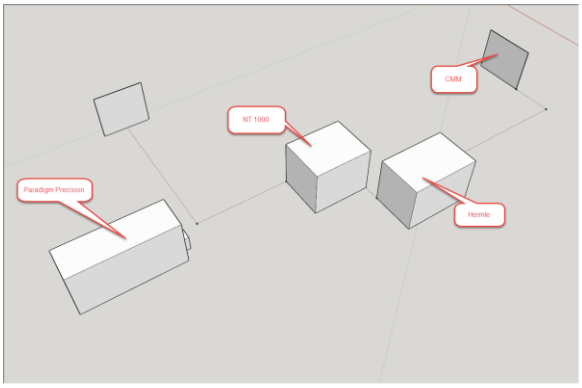

Figure 5: Simplified 3D Model of the Environment

4. RESULTS & DISCUSSION

In this section, the performance of the application and form factors is analyzed. The focus is on tracking and communication in industrial settings, identifying opportunities and gaps in the implementation of AR technology. We ran the application multiple times at different times of day to investigate the influence of lighting conditions.

4.1. Tracking

The majority of image targets were recognized almost instantaneously when the tablet was used. The glasses required shorter distance and almost perpendicular position of the camera to the object. The tablet also provided more stable tracking. This difference in performance can be attributed to the much higher resolution of the tablet's camera.

The image target recognition approach is also sensitive to lighting conditions. Since the illumination of the CCAM's shop-floor is provided by lamps and sunlight, the conditions can change throughout the day. In some cases, during sunny days, the camera was blinded if a window was in the current camera's frame. Again, this phenomenon was more prevalent on the glasses.

Since the image target tracking relies on searching for known patterns in the current camera's frame, shop-floor elements used in this process need to stay relatively invariant. Additionally, if several pieces of the same equipment are available across the facility, an incorrect one can be falsely recognized.

Figure 6: AR Display Using Image Tracking

Radio-frequency identification (RFID) tags as supplementing, and in some cases replacing visual tracking could improve object tracking since for some cases only the general user's proximity is needed to detect what information to display.

4.2. Communication

To enable data exchange, we leveraged the existing communication network at CCAM. Machining data was obtained via an OPC server and converted to XML format, and streamed to the server we had set up for this project. We also implemented an MTConnect data reader and connected it to the test server for testing purposes. The user can see a parameter of his choice (**Error! Reference source not found.**) even when he or she is away from the machine.

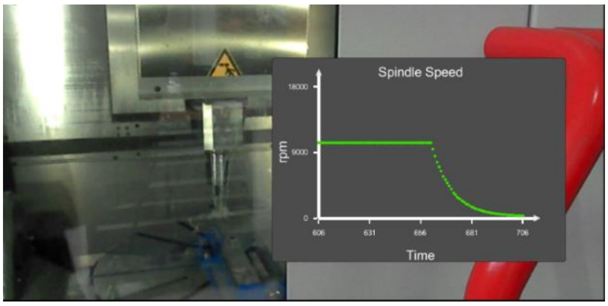

Figure 7: Live Process Information on AR Display

The machinist can also receive critical process-related information once available on the server. In our case study, the application retrieved images of tool wear and the related measurement during M01 stops (**Error! Reference source not found.**).

Figure 8: Server Provided Process-related Information on AR Display

4.3. Content

Providing digital content and information under the just-in-time paradigm is one the most important benefits of using AR in industrial settings. Our application mostly relies on live process information in a textual and numerical form, which is relatively easy to manage in AR. Also, retrieving images is not problematic since there is a lot of widely accepted formats, e.g., jpeg and png. A challenge arises when it comes to handling CAD data. There are many CAD packages being used in the manufacturing domain, each having its own method of describing geometry. In our case, a 3D model of the raw part was created in Siemens NX which uses its own proprietary format which we later converted to FBX – a common format for the Autodesk software family.

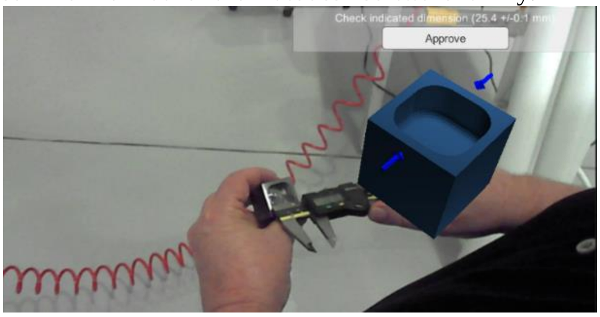

Figure 9: CAD-based 3D Content on AR Display

Businesses incorporating AR will need to provide at least geometric models in one of the standardized file formats, e.g. VRML/X3D. Providing 3D models in these formats is already being practiced by some organizations. This way, workers on the shop-floor can view the part through a regular internet browser. This approach can be also leveraged by AR applications.

4.4. Form Factors

Tests showed that both, handheld and optical see-through HMD, form factors have the potential for industrial applications. They also present limitations to the extent AR could be used.

The majority of the users found the tablet easier to work with since they were already familiar with this form factor. The glasses, on the other hand, required the user to spend some time on learning how to interact with the hardware through the touchpad.

The tablet provided better screen resolution with easier to read text and much better contrast than the glasses. Because the glasses provided a smaller area to display information and digital content, when there too many items displayed, it obstructed the user's view even with limited opacity which can be an issue when used in industrial settings.

The tablet allowed the user to wear safety eyewear, whereas it was not possible to fulfill safety requirements while wearing the HMD.

Both devices require recharging every several hours depending on how much they are used which can be a limiting factor for extended use on the shop-floor.

As far as the glasses are concerned, the scale of the digital content does not match the FOV scale of the real environment, impacting how much information may be displayed at one given time. It is not possible to apply a fixed scaling factor since this phenomenon depends on the distance between the camera and the augmented feature. This is also true for the tablet, however, since the real and augmented world is viewed through the tablet's camera FOV and shown through the tablet's higher resolution display, this issue is not as evident. Newer generations of HMDs could benefit from being equipped with depth cameras, which can greatly compensate for this problem.

5. CONCLUSIONS

In this paper, we investigated the use of AR in industrial settings due to the growing popularity of this technology. We identified several challenges that can affect AR adoption in the manufacturing domain, i.e. robust tracking, communication, content, form factor, and safety.

We developed an AR application for process control using Unity, Vuforia AR SDK, and off-the-shelf hardware to test whether it is possible to provide the user with additional information and content under a just-in-time paradigm, he or she would not have access to otherwise.

Our focus was also on creating a generalized framework for encoding process steps which would allow quick process definition and execution within the AR application. Each process step is defined by up to thirteen parameters which are also input parameters for the algorithm driving the application.

We tested our application at CCAM by applying it to an existing process – machining. The application guided the machinist through the process and provided live process information through an AR form-factor.

Both form factors used during testing exposed associated potential benefits and drawbacks. However, with a rapid progress in AR devices a lot of challenges will be mitigated in the near future.

Advances in enterprise interoperability and ontological context-awareness, which is the next step in our research, will have a major impact on integration of AR with a manufacturing organization.

ACKNOWLEDGMENTS

This work was made possible by members of the Commonwealth Center for Advanced Manufacturing. The authors would like to thank them for their generous support.

REFERENCES

Azuma R.T., 1997. A survey of augmented reality. Presence, 6 (4), 355-385.

Cebulla A., 2013. Projection-based augmented reality. ETH Zurich. Available from: https://www.semanticscholar.org [accessed 10 May 2016]

Colgan A., 2015. The Alignment Problem: How to Position Cameras for Augmented Reality. Available from: http://blog.leapmotion.com [accessed on 29 March 2016]

Daniels D.B., 2014. Cybersecurity Implications in Mobile Device Augmented Reality Applications. GSTF Journal on Computing, 4 (1), 74-76.

Gorecky D., Schmitt M., Loskyll M., Zuhlke D., 2014. Human-machine-interaction in the industry 4.0 era. Proceedings of the 12th IEEE International Conference on Industrial Informatics (INDIN), pp. 289-294. July 27-30, Porto Alegre (Brazil).

Höllerer T., Feiner S., Hallaway D., Bell B., Lanzagorta M., Brown D., Julier S., Baillot Y., Rosenblum L., 2001. User interface management techniques for

collaborative mobile augmented reality. Computers & Graphics, 25 (5), 799-810.
Kagermann H., Helbig J., Hellinger A., Wahlster W., 2013. Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0: Securing the Future of German Manufacturing Industry; Final Report of the Industrie 4.0 Working Group, Forschungsunion. Available from: http://www.acatech.de [accessed on 29 March 2016]
Kanbara M., Okuma T., Takemura H., Yokoya N., 2000. A stereoscopic video see-through augmented reality system based on real-time vision-based registration. Proceedings of Virtual Reality, pp. 255-262. March 18-22, New Brunswick, NJ (USA).
Lee J., Bagheri B., Kao H.-A., 2015. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. Manufacturing Letters, 3, 18-23.
Makita K., Kanbara M., Yokoya N., 2009. View management of annotations for wearable augmented reality. Proceeding of the 2009 International Conference on Multimedia and Expo, pp. 982-985. June 28-July 3, New York, NY (USA).
Mavor A.S., Durlach N.I., 1994. Virtual Reality: Scientific and Technological Challenges. Washington DC: National Academies Press.
McCutcheon R., Pethick R., Bono B., McNelly J., Carrick G., Sulavik C., Waller T., 2016. For US manufacturing, virtual reality is for real. Available from: http://www.pwc.com [accessed 10 May 2016]
River W., 2015. Security in the Internet of Things. Available from http://www.windriver.com [accessed 1 April 2016]
Samini A., Palmerius K.L., 2015. Device Registration for 3D Geometry-Based User-Perspective Rendering in Hand-Held Video See-Through Augmented Reality. Proceedings of International Conference on Augmented and Virtual Reality, pp. 151-167. August 31-September, Lecce (Italy).
Schmitt M., Meixner G., Gorecky D., Seissler M., Loskyll M., 2013. Mobile Interaction Technologies in the Factory of the Future. Proceedings of the Symposium on Analysis, Design, and Evaluation of Human-Machine Systems, pp. 536-542. August 11-15, Las Vegas, NV (USA).
Tsai H.-C., 2013. Safety view management for augmented reality based on MapReduce strategy on multi-core processors. Proceedings of the 13th International Conference on Telecommunications, pp. 151-156. November 5-7, Tampere (Finland).
Wellner P., 1993. Interacting with paper on the DigitalDesk. Communications of the ACM, 36 (7), 87-96.

AUTHORS BIOGRAPHY

Krzysztof J. Rechowicz, Ph.D., is a Research Assistant Professor at the Virginia Modeling, Analysis and Simulation Center of Old Dominion University. He also serves as a researcher and university representative at the Commonwealth Center for Advanced Manufacturing. He previously served as a Postdoctoral Research Associate at Old Dominion University from 2012 to 2014. In 2006, Dr. Rechowicz received his M.Eng. jointly with his B.Eng. in Mechanics and Machine Construction from the Warsaw University of Technology. He went on to receive his Ph.D. in Engineering with a Concentration in Modeling and Simulation from the Old Dominion University in 2012. Dr. Rechowicz's research interests center on applications of virtual and augmented reality, visualization and adequate user interfaces to medicine and manufacturing. Some of his past projects include the development of a haptically-enabled virtual surgical simulator and planner for a minimally surgical procedure that repairs a congenital chest wall deformity. Furthermore, he designed a surgical tool for removing chest implants without the need of larger skin openings. He has also applied his research experience to solve real world problems of the manufacturing industry, and his work has been sponsored by companies like Rolls-Royce, Sandvik and Chromalloy. He has worked on providing visualization for manufacturing processes which allowed to better understand influence of process variables on its outcome, and software applications for machining industry.

Hector M. Garcia, MArch, is a Senior Project Scientist at Old Dominion University's Virginia Modeling Analysis and Simulation Center, in the area of Visualization, Virtual Environments and Virtual Reality, integrating state of the art visualization systems with modeling and simulation applications, and the Scientist most closely involved with the CAVE (Cave Automatic Virtual Environment) on ODU's Norfolk Campus. Mr. Garcia’s expertise include the use of large scale visual simulation display systems, the use of tracking devices, haptic devices and motion bases for immersive virtual reality simulations in the areas of Training, Education and Scientific Visualization. Mr. Garcia has been involved in a variety of research projects funded by NASA, NSF, ONR, and private industry. Most of these projects are interdisciplinary in nature, involving collaborators from multiple university colleges. As his role of Senior Project Scientist at the Virginia Modeling Analysis and Simulation Center, he collaborates with PI’s and Research Scientists in the development of richly interactive Virtual and Augmented Environments for Training.