11th Conference on Learning Factories, CLF2021

Improving MR visualization of digital twins using HoloLens 2

Andreas Künz[a,*], Sabrina Rosmann[a], Gabdelgaziz Sayfutdinov[a], Katrin Paldán[a]

[a]*University of Applied Sciences Vorarlberg, Research Centre User Centred Technologies, Hochschulstraße 1, A-6850 Dornbirn, Austria*

Abstract

One goal of the project described in this paper is to create learning algorithms for machines and robots that lack a precise virtual controller for correct simulations. Using a digital twin approach, the developed mixed reality application aims for an overlay of a virtual robot model with the real world counterpart using Microsoft HoloLens 2 smart glasses. The application should help users to have an inside look into the results of the learning algorithm and therefore supervise and improve those results. The main focus of this paper is the visual representation of the digital twin on the smart glasses. One of the challenges is the level of abstraction and specific use of shaders (program code defining material attributes) to help the user differentiating between virtual and real objects. Therefore different presentation methods are described and evaluated. Study results with 48 persons show that the most abstract representation (wireframe) scores lowest, whereas a half-transparent model works best.

1. Introduction

The research center for User Centred Technologies at the University of Applied Sciences Vorarlberg (FHV) is currently developing a mixed reality (MR) application as part of the FFG funded research project named "concept for machine learning and mixed reality for digital twins of production processes". In the context of Industry 4.0 machine learning algorithms are used to train a virtual representation of a learning factory - the Digital Factory Research Center. As stated in a lot of articles and papers about Industry 4.0, augmented (AR), mixed (MR) and virtual reality (VR) play an important role in the digitalization of industrial processes. According to Kumar and Nayyar [9] AR/VR as well as digital twins are two of the ten key innovations defining Industry 4.0. This paper focuses on the combination of these two technological approaches applying the human-in-the-loop concept used to optimize digital twin simulations. To verify the learning process a person can compare the virtual and real movement e.g. of an industrial robot by seeing the digital representation on top of its physical counterpart using smart glasses. As soon as the behaviour of the digital and real machine diverges too much (e.g. angle difference > 5°, positional difference > 2cm) or the deviation constantly continues to grow the learning algorithm can be restarted by pressing a virtual button. In most AR/MR applications

the real world is augmented by information (text, pictures, 3D models) that is visible in the physical space. Collins et al. [4] even state a realistic and coherent integration of 3D models in the real world as a key element of MR. In this project however, the MR application aims for quite the contrary: the virtual representation seen through a Microsoft HoloLens 2 has to enable users to clearly distinguish between the digital 3D model and the real machine positioned at the same point in space. With a perfect learning algorithm the virtual and real objects overlap exactly (no deviation at all) - but during the learning process the objects most likely differ in position and/or rotation. This paper tries to answer the question: Which visualization approach and abstraction degree of a moving object fosters the recognition of deviations between virtual and real object most clearly?

2. Context

The definition of **Mixed Reality** goes back at least to the mid-nineties. In their reality-virtuality (RV) continuum Milgram et al. [11] subsume augmented reality and augmented virtuality (AV) under the MR term. They define an MR environment as *'one in which real world and virtual world objects are presented together within a single display'*. Azuma et al. [1] base their definition of augmented reality on the aforementioned RV-continuum and highlight these major properties of AR: Alignment of real and virtual objects within a real environment and real-time interaction. As MR is used as an umbrella term to AR and AV these characteristics would also apply to the term mixed reality. According to the thorough paper survey and expert interviews by Speicher et al. [13] 35.3% of the publications and 30% of the experts correspond to the RV continuum and 23.5% use AR and MR synonymous. In this paper, MR is also defined by the two properties listed above. Kritzinger et al. [8] differentiate between digital model, digital shadow and **digital twin** based on the level of data integration between real objects and digital replicas. The digital twin provides an automatic two-way communication between those two, meaning changes to the physical objects are reflected on the virtual one and virtual objects can control their counterparts in the real world. Boschert and Rosen [3] emphasize this two-way communication as an important aspect of digital twins and further define the term as a functional and physical description of a real object. For this paper the most relevant aspect of the definition is the latter part, although the other qualities are also met by the project.

3. Related Work

Tvenge et al. [14] provide a concept using MR in combination with simulation-based learning in learning factories. As mentioned in chapter 1, Collins et al. [4] focus on visual coherence in MR based on occlusion, realistic light and shadows as well as stereoscopy amongst others. They identify the most important challenges for hard- and software developers. Verner et al. [15] use MR for students to learn how to teach robots in an iterative process where they see information like center of gravity, etc. in addition to a 3D digital representation of a real small robot on a tablet screen. In the project described in this paper, virtual parts of the learning factory at the FHV are overlaid onto the corresponding real objects in MR whereas distinguishing between virtual and real is crucial. White et al. [16] define superimposing virtual objects in a place that is meaningful for the visualization and adds additional context and information as "situated visualization". Kalkofen et al. [7] analyze the specific challenges and problems for these kinds of augmented visualization and declare the representation of physical parts through outlining, highlighting, lowlighting or using a ghost stylization as one of the strategies to ensure that both virtual and real objects can be differentiated distinctly. Zollmann et al. [17] focus on visualization aspects of MR in several different areas of application and classify characteristics of AR visualization techniques. They list several dimensions relevant for specific thoughts about the representation of superimposed content: purpose of the visualization, data visibility, virtual cues, data filtering and abstraction as well as compositing. Nölle [12] provides a variety of very specific presentation approaches used to compare between real and overlayed virtual objects in the car industry. The most promising methods are described in more detail in chapter 4.

4. MR Visualization Techniques

Regarding the representation of 3D models in MR, balancing the aspects perception and performance is of utmost importance. To provide a flicker free and smooth representation, 3D materials provided by the Mixed Reality Toolkit

(MRTK) shader set from Microsoft [10] for the MR content creation tool Unity3D are used. Nölle [12] describes some interesting overlay techniques from which two specific ones were chosen for this project: transparency and wireframe. Additionally, our MR application provides an outline material as mentioned by Kalkofen et al. [7]. In the end all different approaches could be combined and adapted to the real environment as far as lighting, color, etc. is concerned.

4.1. Wireframe

A wireframe visualization means that a 3D model is represented by the edges that define the shape of the model. This kind of representation goes back to the early days of computer graphics and has also been used to overlay digital models with real objects decades ago, for example in 1993 by Drascic et al. [5], who used that method to represent future movement of an industrial robot using AR displays. The look of the wireframe can vary strongly, though, as it is highly dependant on the shader details and the topology of the model, meaning the way the surface parts (polygons) are aligned. The wireframe version used in the study described in this paper can be seen on the second robot in figure 1. The robot arms are visualized as flat triangles whereas the hinges are much more pronounced by using thicker and more detailed lines.

4.2. Outline

The standard outline look provided for the HoloLens 2 features a colorless flat surface surrounded by the outlines as seen in figure 1 on the third robot. Alternatively, not only the lines defined by the outside of the overall model might be shown but also some details of the separate parts. Changing the thickness and color of the outline improves or reduces visibility, as well as in- or decreasing the opacity of the interior flat gray area. A lot of different variants were created for this project and in the end an orange outline surrounding a gray area was used in the study described in chapter 5.

4.3. Transparency

The base for this visualization is a standard diffuse material with a given opacity. The transparency value highly affects the visibility of the virtual and real objects, so a compromise has to be found to make both objects easily recognizable at the same time. This, however, is also determined by the lighting condition of the real environment and the material qualities like shininess, brightness and color of the virtual and real objects. In the shown example (figure 1, robot on the very right) the virtual object has a stripe texture, but for a better visual distinction it might also be helpful to experiment with different color effects and transparency variations. In combination with other material qualities like shininess or structure as well as the degree of transparency the possible variations of a "transparent material" are almost endless.
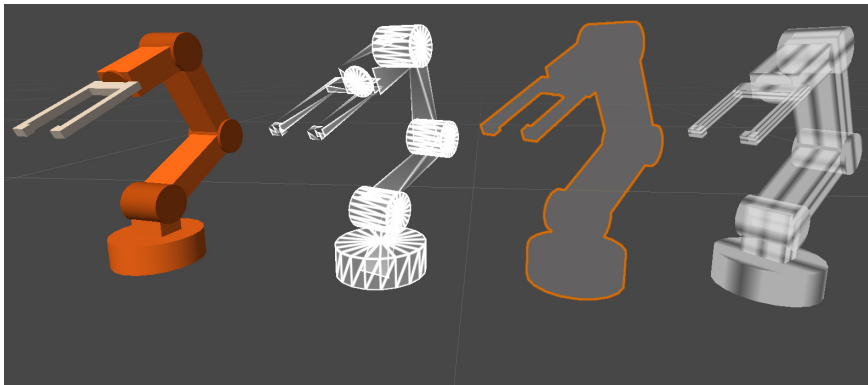

Fig. 1. Visualization methods (f.l.t.r.): shaded base model, wireframe, outline, transparency

5. Evaluation And Results

To define which of the aforementioned visualization techniques fulfills the goal of easily recognizing deviations of a digital twin from a real object best, a study with 48 persons was conducted. Due to the Covid-19 pandemic it was not possible to carry out a trial using the final interactive MR application with the HoloLens 2 in the learning factory. The final study setup consisted of:

- A small Arduino robot (TinkerKit Braccio controlled by its respective Arduino library) representing a part of the learning factory
- Screen captures of the MR scene with the robot and three different superimposed virtual models
- An online survey platform with all three visualization techniques mentioned in chapter 4
- The System Usability Scale (SUS) [2] and AttrakDiff [6] to evaluate each visualziation approach

Of the 48 test persons 68,7% (n=33) were male and 31,2% (n=15) female, 70,8% (n=34) younger than 30 years old and 29,2% (n=14) between 30 and 61 years. Half (n=24) stated having no experience with AR or MR at all, whereas 35,4% (n=17) declared at least some experience and 14,6% (n=7) a lot of experience. The SUS score is defined by questions on how complex and how useful the different visualizations are for recognizing deviations between the real and virtual robot. Furthermore the users had to estimate the ease of use of the MR application what was of course difficult to do without using the HoloLens (what was planned but not possible due to Covid-19). Male and female did rate the different visualizations almost the same and with no statistical significance. The wireframe model got a score of 51,28 from male users and 51,83 from female. The outline model got 45,15 by males and 46 by females and the transparency model 54,84 by males and 52,66 by females. While there is also no significant difference in the SUS score depending on age, table 1 shows the different SUS scores based on the MR experience (1=none, 5=a lot). A score of around 40 means poor usability, 52 means OK but still marginal and an acceptable usability would start at 70 points [2]. The mediocre scores of this study most likely derive from the fact that quite some questions focus on interactivity but it was not possible to try out the interactive prototype. However, the relative difference of the results for the three visualization approaches still give some interesting insights on how useful each abstract level is to recognize deviations between digital twins and real factories. The results allow two interesting conclusions:

- The visualizations are ranked equally independent of the MR experience: the transparency model performs best (M=54.687, SD=10.967, n=24 for persons without any experience; M=53.64, SD=6.425, n=24 with experience), the wireframe model is second (M=54.062, SD=7.216, n=24 for persons without any experience; M=48.854, SD=6.297, n=24 with experience) and the outline model gets the worst score (M=47.18, SD=12.386, n=24 for persons without any experience; M=43.645, SD=6.254, n=24 with experience).
- The more abstract variations get a lower score from users with (at least minimum) MR experience compared to those without any experience. Unrelated samples T-tests show no significant difference for the transparent and edge model. The mean of the wireframe visualization significantly ($t(46)=-2.664$, $p=0.0011$) differs by 6.21 points on the SUS score. Although users with more MR and 3D experience were expected to evaluate the more technical visualization approaches better than inexperienced persons, experienced users assessed the wireframe model worse than users without any experience.

Table 1. SUS mean score based on MR experience

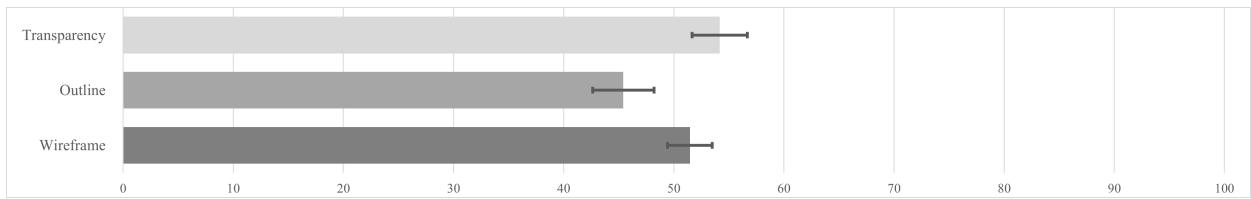| Number of persons	MR experience	Wireframe score (M)	Outline score (M)	Transparency score (M)
24	1 (none)	54,06	47,19	54,69
9	2	50,28	48,61	55,28
8	3	48,44	40,00	51,88
5	4	48,50	42,00	54,00
2	5 (a lot)	45,00	40,00	52,50

Fig. 2. SUS mean score including confidence intervals

Figure 2 shows the overall statistical results of the SUS score. A repeated-measures analysis of variance (assumed sphericity: Mauchly-W(2)=.994,p=.865) shows that the visualization technique has a significant influence on subjective evaluation based on the SUS ($F(2,94)$=18.967, p=0.000, np2=0.288). Bonfferoni-corrected pairwise comparisons depict that the transparency model (M=54.16, SD=8.90) scores significantly (p=0.001) better than the outline model (M=45.41, SD=9.87). The effect size according to Cohen (1988) is 0.63 and corresponds to a strong effect and thus a significant difference of the mean values between transparency and outline visualizations. Between the outline model (M=45.41, SD=9.87) and the wireframe model (M=51.45, SD=7.19) significance can also be assumed with p=0.001 (using a 0.005 level of significance). There is no significant difference (p=0.187) in scores between the transparency model (M=54.16, SD=8.90) and the wireframe model (M=51.45, SD=7.19).

The results from the AttrakDiff survey are shown in figure 3. For almost all aspects the visualization results correlate with the SUS score as far as the ranking is concerned. The transparency model consistently scores lowest and the outline model almost always scores highest (the lower the value the better). The wireframe model is seen very technically (M=4.25, SD=0.81), neutral as far as pleasantness is concerned (M=2.52, SD=1.07), a bit more conventional than inventive (M=2.69, SD=1.07), slightly complicated (M=2.79, SD=1.24), tending to ugly (M=3.35, SD=1.08) and almost neutral concerning liking (M=2.6, SD=0.94). The outline model is evaluated a bit less technical than the wireframe (M=3.87, SD=1.14), less pleasant (M=3.37, SD=1.27), less inventive (M=3.41, SD=1.05), a bit less complicated (M=2.38, SD=1.35), less attractive (M=2.42, SD=1.30) and less likeable (M=3.46, SD=1.25). The transparency visualization is evaluated best, still with a high technical attribution (M=3.56, SD=1.18) and neutral attitude towards originality (M=2.54, SD=1.24), but with positive results for pleasantness (M=1.85, 0.90), simplicity (M=2.19, SD=1.02), attractiveness (M=4.08, SD=1.30) and likeability (M=1.98, SD=1.25).
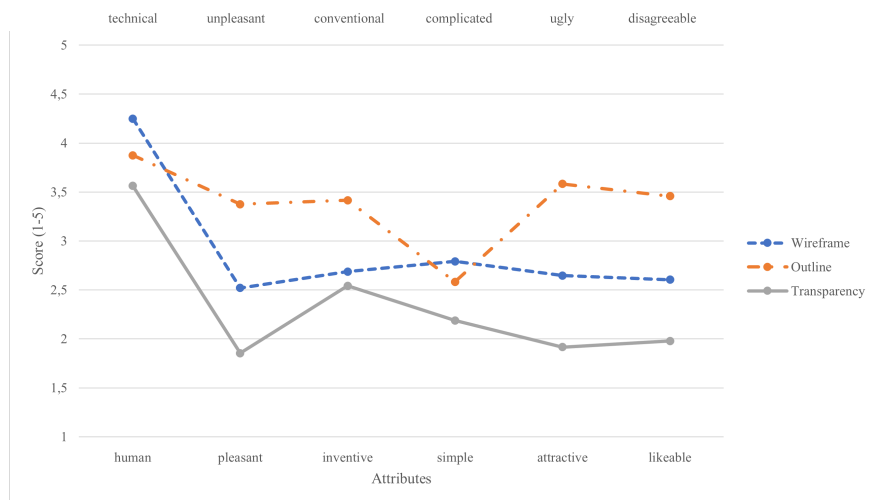

Fig. 3. Results from the AttrakDiff survey. A score of 1 is most often connotated positively

6. Conclusion And Outlook

The survey results clearly state that, independent of age, gender or MR experience, the slightly transparent visualization performed best and the outline model worst. These findings are not only useful in the context of the described project, but also might help improving MR visualization in learning factories and therefore help students understanding different aspects of the industrial environment better. The major problem with the outline method most likely is the opaque area inside the outline that might have obstructed the view of the real model. As already mentioned, the study could only be carried out online using videos. Therefore, the System Usability Scale results can only be used to compare between the different approaches but not to define the properties of the application in general. An alternative survey should be taken into account to answer the questions of this paper more precisely. Furthermore, the viewing angle could not be altered what might influence the impression significantly. Therefore, another trial is planned where not only the outline version uses more transparent parts but the test persons use the interactive MR application on location in the learning factory. In the future even an interactive or a dynamic adaptation of the look might be used to provide ultimate control over the visualization based on the material and color scheme of the real model as well as the environment parameters and the angle of view of the real object.

Acknowledgements

References

[1] Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., MacIntyre, B., Recent advances in augmented reality. IEEE Computer Graphics and Applications 21 (2001) 34–47.

[2] Bangor, A., Kortum, P., Miller, J., Determining what individual SUS scores mean: adding an adjective rating scale. Journal of usability studies 4 (2009) 114–123.

[3] Boschert, S., Rosen, R., Digital twin-the simulation aspect, in: Mechatronic Futures: Challenges and Solutions for Mechatronic Systems and Their Designers, Springer Int. Publishing (2016). 59–74.

[4] Collins, J., Regenbrecht, H., Langlotz, T., Visual coherence in mixed reality: A systematic enquiry. Presence: Teleoperators and Virtual Environments 26 (2017) 16–41.

[5] Drascic, D., Grodski, J.J., Milgram, P., Ruffo, K., Wong, P., Zhai, S., ARGOS, in: Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '93, Association for Computing Machinery (ACM), New York, New York, USA (1993). 521.

[6] Hassenzahl, M., Burmester, M., Koller, F., AttrakDiff: Ein Fragebogen zur Messung wahrgenommener hedonischer und pragmatischer Qualität, in: Mensch & Computer 2003, Vieweg+Teubner Verlag (2003). 187–196.

[7] Kalkofen, D., Sandor, C., White, S., Schmalstieg, D., Visualization Techniques for Augmented Reality, in: Handbook of Augmented Reality, Springer New York (2011). 65–98.

[8] Kritzinger, W., Karner, M., Traar, G., Henjes, J., Sihn, W., Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine 51 (2018) 1016–1022.

[9] Kumar, A., Nayyar, A., si3-Industry: A Sustainable, Intelligent, Innovative, Internet-of-Things Industry, in: Advances in Science, Technology and Innovation, Springer Nature (2020). 1–21.

[10] Microsoft (2021). MRTK Standard Shader — Mixed Reality Toolkit Documentation. URL: https://docs.microsoft.com/de-de/windows/mixed-reality/mrtk-unity/features/rendering/mrtk-standard-shader, accessed: 2021-03-03.

[11] Milgram, P., Takemura, H., Utsumi, A., Kishino, F., Augmented reality: A class of displays on the reality-virtuality continuum, in: Telemanipulator and Telepresence Technologies, SPIE (1995). 282–292.

[12] Nölle, S., Augmented Reality als Vergleichswerkzeug am Beispiel der Automobilindustrie. Dissertation, Technische Universität München, München (2006).

[13] Speicher, M., Hall, B.D., Nebeling, M., What is mixed reality?, in: Conference on Human Factors in Computing Systems - Proceedings, Association for Computing Machinery, New York, NY, USA (2019). 1–15.

[14] Tvenge, N., Ogorodnyk, O., Østbø, N.P., Martinsen, K., Added value of a virtual approach to simulation-based learning in a manufacturing learning factory. Procedia CIRP 88 (2020) 36–41.

[15] Verner, I., Reitman, M., Cuperman, D., Yan, T., Finkelstein, E., Romm, T., Exposing Robot Learning to Students in Augmented Reality Experience, in: Auer, M.E., Langmann, R. (Eds.), Lecture Notes in Networks and Systems, Springer Int. Publishing, Cham (2019). 610–619.

[16] White, S., Feiner, S., Kopylec, J., Virtual vouchers: Prototyping a mobile augmented reality user interface for botanical species identification, in: Proceedings - IEEE Virtual Reality (2006). 133.

[17] Zollmann, S., Grasset, R., Langlotz, T., Lo, W.H., Mori, S., Regenbrecht, H., Visualization Techniques in Augmented Reality: A Taxonomy, Methods and Patterns. IEEE Transactions on Visualization and Computer Graphics (2020).