Virtual Cockpit:
Making Natural Interaction Possible in a Low-Cost VR Simulator

Jeanine Vlasblom, Roy Arents, Ronald van Gimst, Antoine de Reus
Royal Netherlands Aerospace Centre NLR
THE NETHERLANDS

Jeanine.Vlasblom@nlr.nl, Roy.Arents@nlr.nl, Ronald.van.Gimst@nlr.nl, Antoine.de.Reus@nlr.nl

ABSTRACT

Training of military pilots in high-fidelity flight simulators is a common alternative for live training, but these high-fidelity simulators are expensive and location-bound. VR technologies create opportunities for more flexible and low-cost simulator training. However, an essential part of military pilot training concerns managing the aircraft and its systems by physically interacting with the cockpit, which is impossible with the commonly used game-like VR controllers.

This paper describes the development of a VR based tactical training simulation concept in which the pilot can not only see and hear the training environment, but also feel and physically interact with it at a highly realistic level since the system detects and responds to the pilot's input. The technology which enables this immersive match of the physical and virtual worlds, is a combination of interaction detection technologies and 3D-printed cockpit instruments. This allows the pilot to operate the aircraft in a natural way, while being immersed in VR.

The Virtual Cockpit provides the operator with a high-fidelity, flexible and affordable training solution by using innovative, immersive technologies. This is confirmed by positive feedback from pilots in evaluation of the concept.

1.0 INTRODUCTION

1.1 Background

Training in high-fidelity flight simulators has become an essential part of pilot training as an addition to, or alternative for, live training [1]. High-fidelity simulation training can especially be beneficial to train situations which are difficult to practice live, for example high-risk scenarios or scenarios involving classified tactics, or in case no aircraft is available for training purposes. However, these high-fidelity simulators are expensive and location-bound.

Immersive technologies create opportunities for more flexible and low-cost simulators. Although these technologies are not new, they have become accessible to a wider audience over the past decade. Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (XR) are rapidly evolving in terms of resolution, latency, Field Of View (FOV), standardization of hardware integration, and software (API / SDK) provision [2]. Meanwhile, these technologies keep reducing in cost and footprint, while becoming more and more easy to use [3]. AR/VR/XR technologies are already being applied within gaming and entertainment [4], but the maturing technology is likely to affect the future of aviation as well, with simulation training being an obvious candidate [1,5,6].

Zooming into VR, the flexibility and low cost of this technology are mainly due to its small footprint and numerous visualization possibilities:

- **Small footprint**. Whereas high-fidelity simulators use large, expensive (projection) screens and a complete cockpit, the physical mock-up of a VR simulator can be as small as the VR glasses. This makes it easier to use in different locations – even when working from home.
- **Numerous visualization possibilities**. Whereas flight simulators are created for a specific type of aircraft, VR-glasses are not limited to any physical environments. This creates the opportunity to simulate cockpits of different aircraft in the same VR device, or even to create completely different virtual environments without the need for additional hardware components.

1.2 Problem statement

However, there are still some challenges to overcome when using VR as a flight simulation training tool.

- **Resolution and FOV**. In order to control an aircraft, it is essential to be able to read the cockpit instruments and virtual checklists. Therefore, high resolution visuals are imperative when training in a virtual cockpit. At this moment, not all VR hardware is yet equipped with an eye-matching resolution and there are none that combine this with a FOV that is large enough to perform the pilot's tasks without changing behaviour in head and/or eye-moments.
- **Natural interaction**. While the combination of a small footprint with the numerous amount of visualization possibilities facilitates flexibility for simulation training, VR may also change or limit user interaction, thereby limiting the training opportunities. Using the instruments that one would normally use, provides the most natural form of interaction and the highest level of immersion which could be beneficial for training effectiveness [3]. For a pilot this means physically interacting with the cockpit instruments and controls, also during flight simulation training. After interacting, a certain response from the system – e.g. the aircraft is turning left – is expected. When physically interacting with real-world objects, haptic feedback is important to know the interaction happened. Replacing this haptic feedback with visual or auditive feedback cannot significantly improve performance when interacting with objects in a virtual, immersive environment [3].

  There are currently three options in VR to detect the pilot's manual input on the (simulated) aircraft instruments, and to allow translation into the correct simulated response:

  - Handheld gaming controllers are commonly used to detect the user's input in VR, but this is not representative for controlling cockpit instruments and can therefore not be categorized as natural interaction with the physical environment, nor as realistic haptic feedback.
  - VR-gloves are used by some developers to establish the interaction detection [4,7] but there appears to be room for improvement regarding the accuracy and speed of the interaction detection. While gloves resemble a natural interaction much better than gaming controllers, the haptic feedback is still lacking. Furthermore, military pilots would not be able to wear their own gloves.
  - Detect the natural interaction in an actual cockpit or high-fidelity simulator using wired interfaces. This solution, however, has the same disadvantage as high-fidelity simulators: they are location-bound and have a large footprint. On top of that, the Virtual Reality should exactly align with the physical reality, which can be another challenge.
- **Sense of presence**. Another issue is the (in)ability to see your own hands in VR. Since VR headsets typically use opaque displays for visualisation, a direct view of the real world including one's one hands is obstructed, leading to a lower sense of presence in VR. Overall, research indicates that a higher realism of sensory input in a virtual environment increases the sense of presence [8]. Some VR applications use virtual hands that are positioned at controller locations, with assumptions on hand pose. While this works for gaming applications, (flight) simulation training applications may have higher demands depending on the training tasks and objectives.

Two of these three challenges are to some extent related. If it is possible to accurately track the VR user's hands and visualize them alongside a virtual representation of the real world, the user would be able to naturally interact with the real-world objects - which provide haptic feedback. This does, however, require a highly accurate interaction detection and a realistic visual representation of the interaction.

1.3 Related activities

Several research groups have worked on interaction detection by using a depth camera to track the location of the hands and fingers in relation to the physical environment. The recorded image can be used to visualize the user's hands in the virtual reality. The camera used for this set-up is often the Leap Motion [6,9,10], known for its hand tracking functionality. Höll and colleagues [9] used this camera to detect the intersections between the user's hands and the virtual object. The camera image was translated into a simplified 3D model of the hand, which was used to detect the contact point between the virtual hand model and the virtual object. However, the Leap Motion camera did not facilitate the natural interaction the researchers were looking for. Some researchers [10] found that the Leap Motion was less accurate in the detection of grasping and moving objects than their own data glove in combination with the Vive Tracker. Others [6] found that even though hand interactions contribute to a feeling of being immersed, more feedback is needed. In that study [6], the pilots could interact with actual cockpit instruments, but these did not provide the pilot with haptic feedback.

Similar efforts have been made with other cameras in combination with a model to estimate the hand's position, to create a 3D hand model from 21 individual coordinates per hand [11]. While this set-up appeared to be very accurate in detecting hands in motion, this model has not been tested in interaction detection settings [11].

An increased number of VR headsets, including the Varjo XR [12] are incorporating video sensors to allow video see-through on the opaque displays. This allows a more natural perception of the real world surrounding the user, including one's own hands and fingers. To increase the sense of presence and immersion in applications running on such device, a frequently used solution is hand segmentation. Some devices further improve this, thereby moving towards highly realistic visual feedback, by including (stereo) sensors to derive depth information and using hardware that supports high update rates.

To conclude, it appears that the identified challenges could be tackled by using smart camera techniques to detect a natural interaction with cockpit instruments in the real world. The recorded image of the pilot's own hands could then be visualized in VR to create a realistic visual feedback.

2.0 THE VIRTUAL COCKPIT

This paper describes the agile development of the Virtual Cockpit concept by the Royal Netherlands Aerospace Centre (NLR).

The Virtual Cockpit is a VR simulator (see Figure 1) in which a natural interaction with the physical world is possible. The virtual world looks and sounds like the real cockpit, while the hardware feels like the real cockpit. This is possible due to a newly developed interaction detection method, allowing the simulated cockpit to realistically respond to the pilot's input.

Figure 1: The Virtual Cockpit concept.

The Virtual Cockpit consists of three layers: a physical, a virtual and a sensor layer. In the physical layer, the advantage of the small footprint - which is a fundamental aspect of VR - remains, while the challenge regarding the haptic feedback is tackled. In the visual layer, the advantage of the numerous visualization possibilities available in VR is still present, while the sense of presence challenge is dealt with. In the sensor layer, solutions are created to tackle the challenge of naturally interacting with instruments in the physical world. The set-up of the Virtual Cockpit will be explained according to these layers.

While creating the Virtual Cockpit, different hardware has been tested in different configurations (see Table 1). Each configuration consisted of a simple wooden panel, push-buttons to resemble the AH-64 displays, a VR headset with its position tracking sensors, physical flight controls, and interaction detection sensors. All components are either Commercial Off The Shelf (COTS) products or 3D-printed parts, to ensure a low-cost product.

Table 1: Hard- and software used in each configuration.

Config.	Buttons		Sensor(s)	Glasses
1.1	MFD + MPD (push)		Leap Motion	HTC VIVE
1.2	MFD + MPD (push)		Leap Motion + Manus VR glove	HTC VIVE
1.3	MFD + MPD (push)		Manus VR glove	HTC VIVE
2	MFD + MPD (push + click) + toggle		Intel RealSense SR-300	HTC VIVE
3	2x MPD (push + click) + toggle + turn		Intel RealSense D-415	HTC VIVE &

The following paragraphs describe the hardware in further detail.

2.1 Physical layer

The physical layer consists of a simple wooden panel, which was cut to a size large enough to attach both a 3D-printed AH-64 Multi-Purpose Display (MPD) and a bezel of an F-16 Multi-Function Display (MFD), see Figure 2-1. The latter stemmed from a real F-16 Multi-Function Display and therefore resembles the haptic feedback of the actual MFD better. The 3D-printed buttons resemble the MPD better in regard to the distance between and the location of the buttons. This difference in size and matter made it possible to detect possible differences in the accuracy of the interaction detection, and in the natural feel of the haptic feedback.

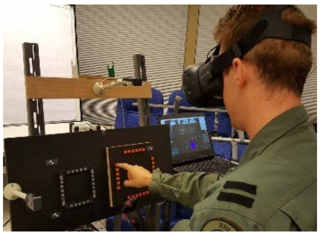

Figure 2-1: Configuration 1.1.

Figure 2-2: Configuration 2.

Figure 2-3: Configuration 3.

Based on the feedback by the operators, the 3D-printed buttons were improved over time to create a more realistic haptic feedback – a more natural 'feel'. This was realized by using a push- and click mechanism (see Table 1), which feels similar to the actual MPD buttons in the AH-64.

In configurations 2 and 3, the cockpit panel was extended with a COTS toggle switch with three positions, which was used in the simulation as an AH-64 Fire Detection/Extinguishing panel switch. In the final configuration, the right MPD display was extended with three COTS turn knobs (one 3-position rotary switch and two stepless turn knobs). One turn knob was used to adjust the brightness of the display. The left display (F-16 MFD) was replaced by a second 3D-printed AH-64 MPD (Figure 2-3) to complete the final configuration.

Lastly, the simulator includes flight controls (collective, cyclic and pedals). In the final configuration the flight controls were connected to a helicopter flight model in the simulation, enabling the pilot to actually fly the aircraft.

For training purposes, the Virtual Cockpit can be extended with an external screen (Figure 2-1) which is placed next to the simulator. On that screen, the instructor can see the pilot's field of view.

2.2 Virtual layer

The virtual layer was created in Unity 3D, in which an Apache AH-64 cockpit was visualized within the environmental surroundings of a virtual island. The displays of the virtual AH-64 could be controlled by clicking on the physical (3D-printed) pushbuttons. In configuration 1.1, the operator's hands were visualized as an artificial virtual "avatar" hand (Figure 3-1), based on the detected location of the operator's hands.

In configuration 1.2 and 1.3, the operator's hands were visualized as a 3D image of the actual hands (see Figure 3-2), which was possible due to using a different sensor. In configuration 2 and 3, this image was enhanced by overlaying the 3D hands with colour video (see Figure 3-3).

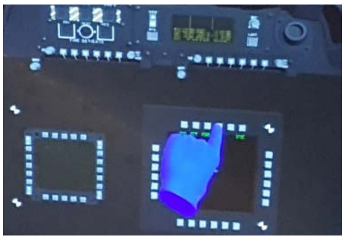

Figure 3-1: Virtual hand.

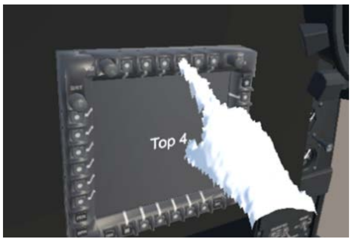

Figure 3-2: Camera-based.

Figure 3-3: Colour image.

The hardware used to visualize the virtual environment was the HTC VIVE headset [13]. During the final evaluation, the HTC VIVE was compared to the Cinoptics COBALT [14] to study possible differences in user friendliness. The main differences between these two headsets are a) the weight (the COBALT is heavier), b) the resolution and c) the field of view (the COBALT's FOV is smaller, but has a larger amount of pixels per degree FOV).

2.3 Sensor layer

Although the physical and virtual environment of the simulator are important, printing push-buttons in 3D and visualizing hands in VR were not the most challenging part of the development process. Developing an accurate and user-friendly interaction detection – without using the classic VR controllers or other COTS products – required more iterations. During the development process, four different sensors were used and tested on accuracy and user-friendliness. In the first configuration, the Leap Motion and the Manus VR glove were used. The other two configurations included different Intel RealSense cameras.

The Leap Motion sensor (configuration 1.1) is a hand tracking sensor based on two infrared cameras, which can recognize and track the operator's hands. Based on this information, the position of all hand joints is deduced, and a virtual hand is visualized.

The Manus VR glove (configuration 1.3) is an actual glove which is worn by the operator. This glove registers the contraction of the fingers and translates that information into a virtual hand-skeleton to detect the position of the fingertips and phalanges. Since the version of the Manus VR glove which was used did not include position tracking of the wrist, the HTC VIVE controller was connected to the arm of the pilot to receive that information.

The Leap Motion sensor and Manus VR glove were also used in a combined manner (configuration 1.2), by merging the sensor output of both devices to detect the position of the operator's finger tips. Errors in sensor data from the first sensor are thereby compensated by the sensor data coming from the second sensor.

In the second and third configuration, an Intel RealSense depth camera was used. This camera provides a 3D image of the environment, which is used to detect the position of the fingertips. In the final development phase, the Intel RealSense SR-300 was replaced by a newer edition: the D-415. This new edition has a higher accuracy regarding the depth-data, resulting in a higher accuracy of the detection of the position of the fingers. Furthermore, this depth information is used to segment the hands from the rest of the cockpit. The RGB data is used to visualize the hands of the pilot in their actual colour in VR.

On top of enabling the interaction detection, the sensor layer can also be seen as the glue which aligns the physical with the virtual layer. This mapping is realized by calibrating red markers on the wooden panel (see Figure 2-2 and 2-3) with corresponding locations in the virtual world. The location of the user in relation to the physical and virtual worlds is calibrated at the beginning of the session by determining the location of the headset. During start-up, the headset is placed in a small container in a fixed alignment position. Similar to the red markers, both the physical and the virtual environment know exactly where the headset is located.

This calibration procedure takes a couple of seconds and results in a perfect alignment between the physical and virtual world, facilitating a smooth transition between the two (as can be seen in Figure 4) and leading to a higher level of immersion.

Figure 4: Illustration of the alignment between the physical and virtual layer.

3.0 METHODS

This section describes the methods used for the development process and evaluations.

3.1 Agile development

The development of the Virtual Cockpit followed an agile approach, including three formal evaluations of the new technological developments with Subject Matter Experts (SMEs). These evaluations included both objective and subjective measures and followed the same format during each evaluation, enabling a comparison of the created technology over time. The first evaluation focused on configuration 1.1, 1.2 and 1.3 (see Table 1); the second evaluation focused on configuration 2, and the final evaluation focused on configuration 3.

3.2 Participants

The Subject Matter Experts which were consulted for the user requirements and evaluations were operational AH-64 pilots. To collect extensive feedback about the functionality and possible value for training, the group of participants was as heterogeneous as possible in terms of technology-eagerness (early-adopters versus criticasters). Each evaluation included the same participants to track the improvements in a reliable manner. In addition to these participants, the final evaluation included another SME who had not experienced the Virtual Cockpit before.

3.3 Evaluation procedure

All three evaluation sessions followed the same procedure.

To minimize the influence of working with an unknown technology, each evaluation started with a familiarisation phase for the pilots to let them get acquainted with VR and interacting in a virtual environment. After that, the pilots had to perform different tasks in the virtual simulator to test the different configurations regarding the physical buttons, VR glasses and sensors.

The performance of these tasks was logged in terms of accuracy by performing the ‘random button test’. In this test, MPD buttons would blink in the virtual world, to which the SME had to respond by clicking on the blinking button. In that way, the amount of correctly registered clicks in relation to the number of blinking buttons reflects the accuracy of the interaction detection. The switch and turn knobs could not be tested with the automatic random button test. Therefore, the researcher asked the SME to turn the knob or toggle the switch to a certain position. The amount of correctly registered interactions in relation to the total amount of interactions reflects the accuracy.

Each evaluation session concluded with a brief semi-structured interview regarding the user experience, the expected effectivity in training situations and the possibilities for future developments.

4.0 RESULTS

In short, the physical environment of the Virtual Cockpit maintains the advantages of VR regarding flexibility and low cost, while solving the challenge of the realistic haptic feedback by using 3D-printed buttons. The virtual environment of the Virtual Cockpit also maintains the advantages of VR, while solving the challenge of the realistic visual feedback by visualizing the actual hands of the pilot. This all is possible because of the newly developed interaction detection technology which is suitable for Virtual Reality purposes. These results are based on both objective measurements and subjective feedback, and are described in more detail in the following paragraphs.

4.1 Resolution and FOV

The resolution and field of view of the VR glasses remained an issue during the final evaluation of the Virtual Cockpit. The FOV of the HTC VIVE was large enough to comfortably fly the aircraft and “feel immersed”, but its resolution was too low to read the displays. On the other hand, the COBALT’s resolution was high, but suffered from a lag when the pilot would move his head. Besides, since the FOV of this headset was too low for the flying task and due to its weight, it was not comfortable to wear for a long time.

At the time of the final evaluation (December 2018), the headsets used by NLR for the Virtual Cockpit were limited to the HTC VIVE and the Cinoptics COBALT. In the following years, these headsets were replaced by next-generation VR and XR glasses with a higher resolution and a higher FOV, like the Varjo and Pimax headsets. No formal evaluations have been carried out with these VR headsets yet, but based on the technical specifications of these new headsets and informal feedback from pilots, it is expected that the previously described challenges regarding eye-matching resolution and FOV can be considered solved.

4.2 Natural interaction

By using the original F-16 MFD, the 3D-printed AH-64 MPD buttons and the COTS switches and turn knobs, the pilots could experience realistic haptic feedback while flying in Virtual Reality. The SMEs explained the urgency by declaring that “the controls should have a level of realism which does not bother the pilots”, which appeared to be true for the MPD buttons, the toggle switch and the turn knobs. The SMEs stated that the haptic realism of the interaction felt “identical to the actual helicopter”. The cyclic stick and the collective lever were not evaluated, since these were not part of the development process for this study.

The interaction detection was evaluated both objectively – in terms of accuracy – and subjectively by SMEs.

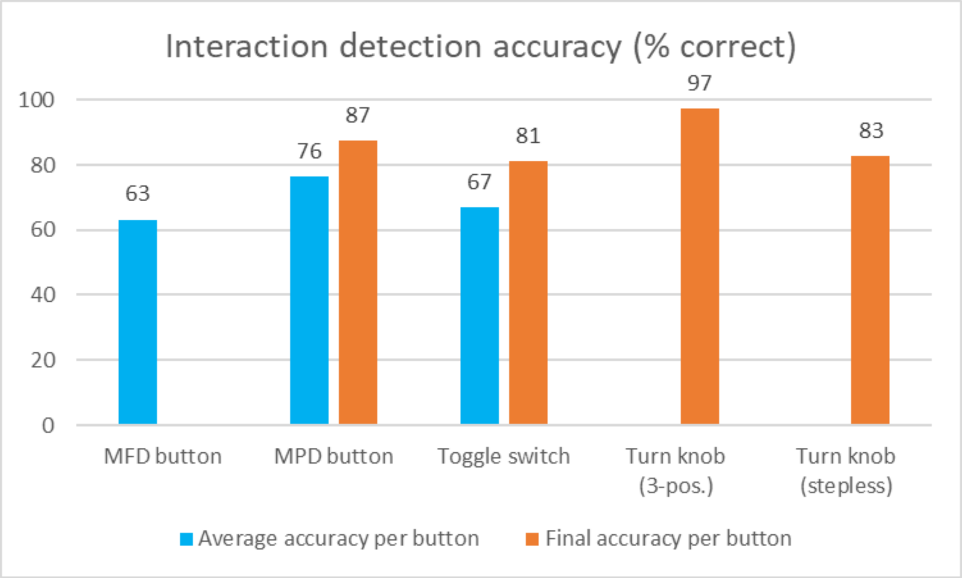

Figure 5: Accuracy of interaction detection per button (average of all configurations and final configuration 3).

The accuracy of the system was measured in percentage of correct detections of interactions. As can be seen in Figure 5, the system was better at correctly detecting the interaction with the 3D-printed AH-64 MPD buttons (over 87% in the final measurement) than detecting interaction with the F-16 MFD buttons or the toggle switch. The accuracy of interaction detection with both turn knobs was even higher (over 97% for the three-position turn knob).

Progress in algorithm development can be seen in the accuracy of the interaction with the MPD buttons and the toggle switch. The SME's feedback on the first configurations, was used to modify the interaction detection, leading to an increased accuracy. The accuracy of these buttons was higher during the final configuration as compared to the average accuracy of all configurations. The F-16 MFD was not used in the final evaluation, and the turn knobs were not introduced before the third configuration. Hence, no data is available regarding the improvement of "their" accuracy.

Diving deeper into the results, the interaction detection mainly improved due to the choice of sensors. Since the Leap Motion sensor only detected "hand gestures" in general, and not the actual position, rotation and length of the fingers, this sensor had trouble accurately detecting the interaction with the MPD and MFD buttons. The Manus VR glove only measured the contraction of the fingers, which could easily go wrong if the glove did not fit perfectly. Another disadvantage of these systems was the virtual hand, which made the interaction not feel natural. The sensor used in the second prototype (the Intel SR-300) improved the interaction detection as opposed to detection by the Leap Motion and the Manus VR glove. Its successor (the Intel D-415) was even more accurate.

Sometimes, a double interaction was detected while pushing that button only once. Similarly, the toggle switch and turn knob were sometimes detected by the system while the pilot was interacting with different buttons. These incorrect interaction detections were more prevalent in the periphery, which can be related to the FOV of the depth camera. Using a camera with a larger FOV or using multiple cameras could therefore enhance the accuracy. Another cause of the incorrect detections might be the alignment between the real and the virtual world. Lag in the virtual environment leads to a (small) discrepancy between the pilot's action and vision. Fast movements might therefore be mispresented. This does not occur when moving at a normal or low pace, and can possibly be optimized in VR.

Despite these incorrect detections, most tasks and training scenarios can be performed with the current set-up. The SMEs stated that the accuracy of the MPD buttons should be close to perfect to perform a tactical training, but the toggle switch and turn knobs are not used that often. Apart from the currently developed technology, the simulation should – of course – also use correct and accurate flight models in order to control the aircraft in a natural way. Note that this was not the objective of our study.

Overall, the SMEs are very satisfied with the interaction in the Virtual Cockpit and enthusiastic about the concept of this simulator.

4.3 Sense of presence

The first reaction of the SMEs when experiencing the Virtual Cockpit was the immediate immersion in the virtual world: *“You see your hands and the cockpit around you”*. Especially a video-captured, coloured representation of the hands – as opposed to artificial virtual hands – was appreciated. The SMEs found it easier to recognize their own hands when they saw their green flying gloves.

Figure 6: An Apache pilot flying the Virtual Cockpit during the third evaluation in the Cinoptics COBALT, while one of the researchers “hitch-hikes” along in the HTC VIVE.

5.0 WAY FORWARD

5.1 Current use cases

While the current use case is a tactical training for AH-64 pilots, its interaction detection technology is generic and can be used for other use cases. It should even be a relatively small step to create a Virtual Cockpit simulator for another aircraft, since the size of the cockpit and buttons are largely similar.

During the development process of the Virtual Cockpit, the potential of VR for training purposes was evident. But over the past years, this potential has transformed into reality: both civil and military institutes have incorporated VR in their training [15,16] and on top of that, EASA recently certified the first VR based flight simulator [17]. Looking at these developments, guidelines on the use of VR in relation to VR sickness would be welcome to prevent or minimalize this side-effect. These could be in line with the advice regarding motion sickness in Flight Simulation Training Devices [18].

5.2 Future trends

While VR seems to be establishing a place in the blend of flight simulation training media [15-17], it is not to be expected that traditional flight training devices will be completely replaced by VR. Ultimately the technology is just there to serve the training objectives and should be fit-for-purpose. However, the introduction of new technology can trigger new use cases, also beyond training. While it is difficult to precisely predict future use cases, there are two domains that seem promising: military mission rehearsal and Concept Development and Experimentation (CD&E).

Mission rehearsal possibilities while being deployed abroad are sometimes limited, since the time between order and take-off is always constrained, and rehearsal means may be scarce in the deployment area. New integrated mission planning tools currently in research and development [19] strive to reduce the time needed for basic planning activities, leaving more time for contingency planning, briefings and rehearsal. These tools may increase the likelihood and amount of alternative plans generated by translating the ever increasing amount of data into information. This allows anticipating on more scenarios with a different likelihood. Such alternative plans can allow a more dynamic response to new threats or opportunities that arise during the mission, but this will rely on a thorough mission rehearsal as well. This is where more flexible, easy to use, and portable VR mission simulator(s) may see new use cases, especially for missions abroad.

Flexibility and ease of use are also important factors for application in CD&E, but with different nuances. There is an increasing need for rapid iterations with tangible intermediate results that can be evaluated with end users. AGILE development approaches tend to support this. The Virtual Cockpit concept has the potential to support this as well. The instrument panel in the concept consisting of 3D-printed buttons, toggle and switches, without wired interfaces or any electronic components, is indicative of this potential. Easily changing one vehicle (type) for another and/or transforming the instrument layout to iterate to an optimal solution is theoretically possible. However, the current implementation of the Virtual Cockpit concept does not fully support this as manually tweaking the hardware, software and calibration is still needed. Nevertheless, this is merely a temporary limitation: there already ideas on follow-up activities that can fulfil the potential for training, mission rehearsal and CD&E purposes, again by the smart combination of physical, virtual and sensor components.

6.0 CONCLUSION

Immersive technologies enable the development of flight simulators with a small footprint and numerous visualization possibilities. This creates opportunities for more flexible and low-cost simulators. While VR is a promising platform which could possibly have a high training value – alongside the more conventional training environments –, there are still some challenges to overcome when using VR as a flight simulation training tool. Specifically, this comes down to the lack of naturally interacting with physical flight instruments, a low sense of presence and a resolution and FOV which do not resemble the human vision.

The Virtual Cockpit aims to tackle these challenges by using a new interaction detection technology which is based on sensor fusion and is suitable for VR purposes. Since the interaction detection is performed by camera sensors, the physical components do not require wired interfaces. Instead, 3D-printed buttons were mounted to a wooden panel to ensure the low-cost of the system.

The development of the Virtual Cockpit followed an iterative process, including regular meetings with Subject Matter Experts (SMEs). Improvements were made based on their feedback, resulting in different configurations of the sensors, buttons and VR glasses used.

The final configuration was evaluated positively. The SMEs were especially impressed with the high fidelity of haptic and virtual feedback, making natural interaction possible in VR. The possibility to see their own hands while flying the aircraft was considered very valuable. The accuracy of the interaction detection of the final configuration was - according to the SMEs - high enough to train regular flight scenarios, but not good enough to train tactical scenarios. A camera with a larger FOV, the use of multiple cameras or an optimized visualization in VR could further enhance the accuracy.

Looking at the main opportunities and challenges of VR simulation training, the Virtual Cockpit retains and enhances the flexibility and usability of VR:

- In the **physical layer**, the advantage of the small footprint remains, while the challenge regarding the haptic feedback is tackled by enabling the pilot to interact with 3D-printed buttons and Commercial Off The Shelf flight instruments.
- In the **visual layer**, the advantage of the numerous visual possibilities available in VR is still present, while the sense of presence is improved by visualizing the pilot’s own hands in VR.
- In the **sensor layer**, a newly developed interaction detection technology was created to tackle the challenge of naturally interacting with instruments in the physical world.

The introduction of the new interaction detection technology can trigger new use-cases for training, but also to support military mission rehearsal and Concept Development and Experimentation (CD&E).

In conclusion, the Virtual Cockpit is a VR simulator in which the pilot can see, feel and naturally interact with a low-cost but high-fidelity training environment, due to newly developed interaction detection technology.

APPENDIX A. REFERENCE SECTION

[1] Valentino, K., Christian, K., & Joelianto, E. (2017). Virtual reality flight simulator. Internetworking Indonesia Journal, 9(1), 21-25.

[2] Cuervo, E., Chintalapudi, K., & Kotaru, M. (2018). Creating the perfect illusion: What will it take to create life-like virtual reality headsets?. Proceedings of the 19th International Workshop on Mobile Computing Systems & Applications, 7-12.

[3] Bassano, C., Chessa, M., & Solari, F. (2020). A Study on the Role of Feedback and Interface Modalities for Natural Interaction in Virtual Reality Environments. VISIGRAPP (2: HUCAPP). 154-161.

[4] Minh, V. T., Katushin, N., & Pumwa, J. (2019). Motion tracking glove for augmented reality and virtual reality. Paladyn, Journal of Behavioral Robotics, 10(1), 160-166.

[5] Aslandere, T., Dreyer, D., Pankratz, F., & Schubotz, R. (2014). A generic virtual reality flight simulator. Virtuelle und Erweiterte Realität, 11. Workshop der GI-Fachgruppe Tagung Band, 1-13.

[6] Martinsson, T. (2019). Evaluation of solutions for a virtual reality cockpit in fighter jet simulation. Human-Centered systems - Linköping University, 34.

[7] Yavrucuk, I., Kubali, E., & Tarimci, O. (2011). A low cost flight simulator using virtual reality tools. IEEE Aerospace and Electronic Systems Magazine, 26(4), 10-14.

[8] Dinh, H. Q., Walker, N., Hodges, L. F., Song, C., & Kobayashi, A. (1999). Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments. Proceedings IEEE Virtual Reality, 222-228.

[9] Höll, M., Oberweger, M., Arth, C., & Lepetit, V. (2018). Efficient physics-based implementation for realistic hand-object interaction in virtual reality. 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), 175-182.

[10] Liu, H., Zhang, Z., Xie, X., Zhu, Y., Liu, Y., Wang, Y., & Zhu, S. C. (2019). High-fidelity grasping in virtual reality using a glove-based system. 2019 international conference on robotics and automation (icra), 5180-5186.

[11] Ban. (2020). MEgATrack: Monochrome Egocentric Articulated Hand-Tracking for Virtual Reality. Shangchen Han - Korea University.

[12] Olsson, T., & Ullberg, O. (2021). Mixed Reality for Gripen Flight Simulators. Linköping University.

[13] HTC. (2021). Vive - Specs & Details. Retrieved on: August 24, 2021. https://www.vive.com/eu/product/vive/

[14] Cinoptics. (2014). COBALT. https://cinoptics.com/wp-content/uploads/2014/08/COBALT-2014.pdf

[15] KLM. (2020). KLM Cityhopper introduces Virtual Reality training for pilots. https://news.klm.com/klm-cityhopper-introduces-virtual-reality-training-for-pilots/

[16] AirForce Magazine. (2020). USAF Brings Pilot Training Next to Regular Training in Experimental

Curriculum. https://www.airforcemag.com/usaf-brings-pilot-training-next-to-regular-training-in-experimental-curriculum/

[17] EASA. (2021). EASA approves the first Virtual Reality (VR) based Flight Simulation Training Device. https://www.easa.europa.eu/newsroom-and-events/press-releases/easa-approves-first-virtual-reality-vr-based-flight-simulation

[18] EASA. (2021). Use and benefits of simulators. https://www.easa.europa.eu/community/topics/use-and-benefits-simulators

[19] de Reus, A. J. C., Vlasblom, J .I. D., Arents, R. R. D. & Oostrom, R. J. A. (2021). 5th Gen Mission Planning: Integrated Systems and Algorithms. NATO MSG Conference, Amsterdam.