A Literature Review and Proposal Towards the Further Integration of Haptics in Aviation

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Abstract. Flight simulator training is essential for aircraft pilots to learn and maintain the ability to fly specific aircraft for both commercial and defence purposes. With recent advances in extended reality, the implementation thereof has made its way into proposed simulated flight training protocols. In conjunction to the advent of extended reality, research into the use of haptics or the sense of touch within VEs has accelerated. A few challenges persist within simulation training including training effectiveness, level of immersiveness, and the manageable exposure duration per training run. Extended reality experiences face similar challenges. The field of haptics might provide solutions for these challenges. Thus, this paper reviews the state-of-the-art of haptics, current challenges, and possible future applications within aviation simulation and training. It is found that research with respect to the integration of haptics in aviation training and simulation is not yet mature. A lot of potential exists for research into the improvement of training effectiveness, performance and immersiveness within extended reality based simulation for flight training and maintenance engineering purposes via haptics. Based thereupon future work is suggested to look into 1) decreasing simulator sickness by simulating and synchronizing expected real life perturbations within flight simulation via haptic wearables 2) simulating a sense of physical flight within a static simulator set-up by leveraging self-motion 3) enabling physical interaction of aircraft parts digital twins for improving extended reality based maintenance engineering performance by utilizing haptic wearables.

Keywords: Human-Machine Interaction · Tactile and haptic interaction · Multimodal interaction · Training education and tutoring · Simulator sickness

1 Introduction

Haptics refers to the sense of touch when manually interacting with the environment which is either real, virtual or a mixture thereof, via self or machine [79]. Haptic technology spans a vast array of different modalities, applications,

as well as possibilities [15].

Simulator training is essential for the education of pilots, as well as for maintaining their skills without having to make use of a physical aircraft, potentially endangering the crew and possible passengers, while cutting down costs and carbon emissions in the process [4][42][12]. A whole plethora of different flight simulators exist where their cost and fidelity (including realism), both often positively related to one another, ranges from low to high [41][50]. With the advent of Extended Reality (XR) a couple of decades ago, there has been a steady rise in different affordable commercial-off-the-shelf (COTS) devices the past few years. Alongside, came an increase in appeal for its usage within the academic field as a research tool [10]. This trend has also sparked interest in the development of lower-cost, immerisve flight simulators using XR devices [26][37].

XR is an umbrella term that encompasses virtual reality (VR), augmented reality (AR) and mixed reality (MR), which can be categorized even further based on hardware. VR makes use of a full Virtual Environment (VE), AR uses a mixture of real world and virtual content, whereas MR is a mixture of VR and AR [63]. Currently, most commercial XR devices focus mainly on providing visual and auditory experiences, and focus less on haptics. Haptics, or the sense of touch, have found their way into everyday commercial items, such as smartphones and video game consoles [91] [53]. Other industries wherein implementations of haptics have been introduced include the medical field [28], automotive [94], nuclear [62], manufacturing [90], and maintenance [60].

XR implementations within flight simulators also exist. Some examples are seen in figure 1. Immersiveness plays a vital roll in effective pilot training within flight simulators. Since humans perceive the real world via multi-modal sensory input, it has been argued that adding haptics will elevate immersiveness in XR experiences [61]. I.e., it has been suggested that haptics have the potential to enhance presence in VEs [21]. Thus, the question arises as to how and to what extent haptics can be used within XR aviation training and simulation, and whether it leverages any potential benefit in improving immersiveness and training effectiveness. To answer the raised question, this paper reviews the state-of-the-art of different categories of haptics, current applications in aviation, discuss our findings and current open challenges thereof, future work based on identified research challenges, and our concluding remarks in sections 2, 3, 4, 5 & 6 respectively.

2 Categories of Haptics

Haptics can be categorized into two main groups: kinaesthetic and cutaneous. Kinaesthetic feedback, refers to the sensation of force. Cutaneous feedback mostly refers to the sense of touch, of which vibrotactility is an example [73]. As the field of haptics spans a broad spectrum, haptics are categorized per overarching research area within this section.

Section 2 discusses tele-haptics and haptic shared control, surface haptics, haptic wearables, multi-modal haptics, and mid-air haptics respectively. Within

Fig. 1: From left to right: NLR Virtual Cockpit, NLR VR Motion Simulator, NLR Helicopter Pilot Station

each category a further distinction is made whether task performance or immersiveness is improved.

2.1 Haptics in Teleoperation & Shared Control

Teleoperation refers to remote manual control of electronic devices. Remote control of an unmanned aerial vehicle (UAV) is an example. Such systems are costly, and mostly require high precision as there is a need for a sophisticated feedback system [23]. Traditionally teleoperation makes use of cameras to provide visual information to the human operator [75]. However, visual information alone proves insufficient for avoiding unwanted collisions [56]. Research into providing realistic haptic feedback for teleoperation to counteract said problem extends even to space applications. [58]. COTS haptic controllers such as the Omni Phantom 3D provide 6-DOF force feedback [76]. Over the past decade research into providing manual control guidance using haptics, or haptic shared control (HSC), has been conducted [2]. [9] found better performance at worse transparency for HSC in teleoperated robot manipulation tasks. [27] implemented a haptic feedback system for simulated teleoperated maintenances tasks for nuclear fusion reactors. HSC has some well documented research within the automotive industry [59][40] [92]. [51] proposes a framework for collaborative steering as a means of communicating human intent of desired trajectory in a highly automated vehicle using HSC.

2.2 Surface Haptics

Over the past few years, researchers have successfully managed to implement the sensation of feeling different types of surfaces, including smooth and rough textures [38]. All different types of surface interactions and texture simulations are modulated by means of altering the vibration amplitude and frequency, per simulated surface texture, as done in [7].

Surface haptics is perhaps the most well known field of haptic research. Research into the use of localization of vibrotactile feedback e.g. by means of using piezo electronic in the periphery of either digital and/or clear glass displays is present [55]. Other techniques for localized haptic feedback include computational focussing methods such as elastic wave focussing [64].

Surface haptics can be used to render either sliding or mechanical clicking sensations on flat surfaces, mostly done via vibration feedback. [71] researched haptic representation of different types of mechanical buttons for implementation in digital touchscreens. These included latch buttons, toggle switches and push buttons were simulated in decreasing order of fidelity. It was concluded that the kinaesthetic tactile feedback associated with physical mechanical switches can not yet be haptically rendered in flat surfaces.

2.3 Haptic Wearables

Haptic wearables are haptic devices worn on the human body and have been researched extensively [87]. Most are intended for the hands, as these are the most subjective body part of the human to discern kinaesthetic amd cutaneous feedback [15].

Commercial hand wearables are often bulky or obstructing some parts of the hand needed for real-world object manipulation. Examples are the SenseGlove Nova and the Manus Prime 3 [85][14]. [81] developed a light-weight haptic glove that does not obstruct the palmar side of the hand. By making use of electronic stimulation on the backside of the hand and wrist, tactile feedback on 11 distinct locations on the palmar side of the hand is rendered, allowing unobstructed physical interaction. This development proves to be hopeful in constructing smaller, unobtrusive, and lightweight commercial haptic gloves.
[82] proposed a foldable finger wearable. Providing kinaesthetic feedback, the wearable can partly fold away, freeing the finger for physical interaction.

Full-body haptic suits also exist [43]. [78] attempted to link a flight simulator running X-Plane with the bHaptics TactSuit for future research purposes looking into full-body haptics and flight simulators, the concept suffered latency issues.

A rather unexplored field is the use of head-haptics. [89] proposed multimodal haptic feedback via vibration motors and thermal sources within a modified HTC Vive Head Mounted Display (HMD). Results indicated that multimodal feedback positively increased enjoyment and immersiveness within a VE.

Fig. 2: From left to right: Manus Prime 3, Senseglove Nova & Experimental Haptic Glove by [81]

2.4 Multi-modal Haptics

It is believed that to allow for full immersion within VE, more sensory modalities need to be provided. Mulsemedia focusses on multi-sensory media representation to enhance the immersiveness thereof including the addition of olfactory, thermoceptic and haptic feedback[80]. Other modalities such as wind have also been researched [77]. [54] looked into the use of gaze-tracking vignette, a first person field of view with body part representation and wind and vibration feedback to study mitigation effects on cyber-sickness. No direct effects of wind were found, but lower heartrates were logged. [46] confirmed the ability to induce perception of non-thermal tactile cues via localized heating of a haptic display. [33] researched the simultaneity of thermal-tactile stimuli and found that distinction between either is perceived best when the thermal cue precedes the tactile one. These findings show the ability of enhancing tactile cues via localized heating by using synchronized vibrotactile cues.

2.5 Mid-air Haptics

Mid-air haptics (MaH) focusses on providing vibrotactile feedback without externally worn devices. MaH makes use of an array of ultrasonic transducers, which provides localized vibrotactile feedback by means of creating a focal point of ultrasonic soundwaves, which are perceived by the human as a sense of touch [30]. Although weak, it can be perceived notably and can therefore be used to render clicking, and sliding sensations. [6] proposed selective stimulation of human mechanoreceptors via air pressure for implementation in VR. MaH can be generated from heat conduction from porous silicone [74], or with an array of ultrasonic transducers to create a vocal point with air-pressure [30] [29]. [49] proposed a concept for a floating virtual screen with MaH feedback. The mid-air projected images are created via the use of a transmissive mirror that display images in front of the mirror, where the vocal point of MaH coincides with the location of the projected images. A proposed concept of using MaH for full substitution of physical controls in flight simulators was made by [22].

3 Haptics in Aviation

Haptics are discussed further within the context of aviation. Section 3 discusses haptics for piloting tasks, haptic aiding implementations for aviation maintenance, and haptics for mitigating cyber- and simulator sickness.

3.1 Haptics for Piloting Tasks

Haptic Feedback for Improving Task Performance [3] compared indirect haptic aid (IHA), direct haptic aid (DHA), and no haptic aid to one another on the basis of pilot performance in a tele-operated task controlling an UAV. IHA involves vibrotactile haptic cues to retrieve system information. Results indicate

DHA to be less natural and aiding compared to IHA. For maintaining level flight, having no haptic feedback had the highest performance. DHA was considered to be the most helpful aid, but only after familiarization.

[52] experimentally compared the effects of IHA, DHA and no haptic feedback on pilot performance in a manned flight tracking task. Simulation restuls found pilots to be more compliant with DHA. However, both IHA and DHA increased tracking performance after adaptation. IHA outperformed DHA. In turn, DHA reduced pilot physical effort.

[45] proposed a haptic aiding system for UAV contro. Tested for simulated longitudinal flight incorporating an ascending, descending, and altitude maintaining task, results indicate different levels of haptics to have significant task dependent effect on pilot performance. No feedback for altitude hold tasks, exaggerated force feedback for gaining altitude, and realistic force feedback for descending. Overall, haptic feedback improved immersion, deemed essential for the transition from simulated to real-life flight.

[93] proposed the use of haptic feedback for aiding an aircraft landing task to mitigate landing illusions associated with incorrect perception of visual cues. Pilots relied more on haptic compared to visual cues, implying that haptics can aid pilot performance during low visibility flight.

[26] conducted a study with 120 beginner level pilots. Comparing VR-, computer-based simulation, and no training. No difference in results were found between VR- and computer-based. Subjective results indicate participants judge individual performance to be better in VR . VR was regarded as readily available for home-use at reasonable cost, potentially helping flight-training preparations at home. A downside to VR was the inability to physically manipulate flight instruments.

[17] proposed a pilot intent estimator for inferring the most probable flight path trajectory, solely using pilot control input. [5] proposed a haptic aid system which adapts to the pilot input and performance. [16] combined [5] and [17] to make a 2 DOF HSC system to decrease helicopter pilot workload. Results from 1 expert and 13 general participants were positive and significant. Half of the participants performed flight trials better with haptics versus none. Haptic aid was more significant in longitudinal compared to lateral control, but significantly reduces overall pilot control effort.

Haptic Feedback for Increasing Safety [8] proposed the use of haptic support in conjunction with a perspective flight-path display to minimize heads-down time of pilots associated with using said display. Results indicated that pilots were able to accurately follow a flight path with noticeably more heads-up time when a minimal amount of haptic feedback was provided. The possitive effect of haptic aid became stronger with increased task difficulty. Mental workload significantly decreases when the amount of haptic feedback increases. Haptic feedback thus allows for a longer heads-up time of pilots, increasing spatial awareness of the pilot during aircraft trajectory following tasks.

[84] proposed a haptic feedback system for flight envelope protection. Three

different concepts for haptic aid in flight envelope protection were proposed and evaluated [83]. The first method utilizes guidance and discrete feedback as proposed in [83]. The second method used asymmetric vibrations via sawtooth waves. The third used HSC, as discussed prior in section 2.1. Results for the first concept showed no significant statistical results with respect to an increase in pilot performance, safety or awareness. As opposed to this, subjective pilot interviews proved the contrary, thus insinuating that the stated benefits can potentially be attained with the use of haptic feedback and discrete feedback. The second concept showed that no effects were found for improving performance or safety, but indications were present that it did improve the learning rate of the participants. The third concept showed that haptic shared control increased safety when used from the beginning. However, it was observed that if haptic assistance dissapeared afterwards, an over-reliance and instantaneous increase of workload presented itself as an after-effect.

[70] supplemented the work of [84] by adding visual indicators for the haptic feedback system on the aircraft's digital flight instruments for communicating flight envelope boundaries to the pilot. Although objective results were not conclusive, subjective results indicated that haptic feedback cues were interpreted more correctly with the visual aid of the updated display.

Haptic Feedback for Increasing Immersiveness [69] looked into the learning effects of a full-body haptic controller for UAV control. The vest utilizes inflatable pockets of air indicating indicating centripetal acceleration of the drone on the human body and cable-driven haptic guidance [68]. This research focusses on the realization of an intuitive haptic drone-controller using upper body input, to render the sensation of flight within VR.

From [88] it is found that motion within flight simulators seem important for some scenarios. Effects for helicopter, disturbance tasks and inexperienced pilots were stronger than those for fix-winged aircraft manoeuvring and expert pilots.

[18] referred to the sensation of motion purely via visual stimulus as induced motion. In other words; visually induced motion, or self-motion is the sensation of moving one's body while remaining stationary. Self-motion could be leveraged as a possible substitute for mechanical motion-based simulators. [13] proposed the use of a kinesthetic HMD within a VR flight simulator that induces self-motion via force feedback provided by a haption haptic device. Results indicated that the use of force-feedback within the HMD improved egocentric sensations of self-motion compared to a purely visual VR experience.

3.2 Haptics for Aircraft Maintenance Tasks

Haptic Feedback and XR for Simulated Maintenance Training within Aviation [1] utilized VR in combination with a table-top mounted force-feedback haptic controller for an aircraft maintenance simulation experiment. The results were encouraging, however more experimentation and possibly further advancements in haptic and XR technology were needed in order to test the perceived

benefit of the combination of both, for simulation training.

[11] researched a haptic VR set-up for an aerospace grade carbon fiber reinforced polymer panel drilling task. Comparison between beginner and experts indicated that the VR system was usable for training beginners, cutting down costs as opposed to having to train on real panels.

It has to be noted that research into the use of XR and haptics within the scenario of aviation maintenance is not yet mature and more research is needed. However as aircraft maintenance engineering training procedure focuses on specific tool-based skill learning, a lot of research findings can be adopted from a larger body of literature work found in fields such as industrial assembly and medicine.

Relevant Research from other Fields [24] looked into several different set-ups for utilizing force-feedback haptics in simulated assembly tasks for educational purposes. They discussed the use of VR with haptic gloves for hand tracking and gesture recognition while using a real physical tool or model. Another method was the use of a physical model of a tool attached to a haptic manipulator. Lastly, as another alternative a robot's end effector was used to simulate the surface of a virtual object. [24] argued that the addition of tactile feedback was necessary for VEs to be deemed sufficiently useful for effective training of future operators. [31] conducted a research testing a haptic-based, mouse-based and traditional-based group of 24 participants in total for a digital assembly task. Results indicated that the use of a physics engine and haptics was not significantly different from the traditional training group with respect to training time. The mouse-based group was significantly slower and did not provide the same manner of familiarization as the haptics group, even though results with respect to learning the assembly sequence did not differ amongst the three tested groups. [25] made a systematic literature review of 86 papers in total, researching the use of XR in industrial maintenance. Therein, 8 papers where identified that utilized some sort of haptic feedback in combination with XR and maintenance engineering. The overall takeaway of [25] is that haptic feedback is deemed important for maintenance. Research indicates that the inclusion of haptics has a positive benefit with regards to situational awareness and operator performance.

Research within the medical field is overall positive towards the use of XR and/or haptics. However, a meta-analysis of 422 papers within said field involving XR and haptic interfaces concluded the available research evidence to be inadequate in supporting the perceived benefits thereof due to limited testing with surgeons, and overall poor experiment design [44].

3.3 Haptics for Mitigating Simulator Sickness

What is simulator sickness? SS is resemblant to motion sickness (MS), however the severity of the syptoms as well as the underlying causes differ. Due to comparable reasons to SS, cybersickness (CS) can occur while immersed in VEs.

In short, SS or CS is a visually induced sensation of sickness and will be used interchangeably. This comes mostly due to visual-oculomotor and vestibular-oculomotor discrepancies. [39] details a large list of possible variables influencing the onset and experience of SS. A subjective method for studying SS is the Simulator Sickness Questionnaire (SSQ) [35].

[19] conducted a review of 39 articles that found evidence with respect to the progression of SS, possibility of adapting for SS in VR and persistence of symptoms after exposure to VR. The two most widely cited reasons for SS are the Sensory Conflict Theory (SCT) proposed by [65] and the Postural Instability Theory (PIT) proposed by [66]. The first theory attributes the onset of SS due to conflict of different modalities of sensory input, mostly being visual and vestibular in origin. In short; the SCT attributes SS to visuo-vestibular conflict. [66] argued against [65] on the grounds that sensory conflict is a common natural occurence. [66] therefore proposed the PIT, which states that the human experiences symptoms of SS in the case that the body has not yet adapted to environments in which it can maintain adequate postural stability. This theory infers the possibility of adapting to VEs and eventually overcoming SS. To summarize, it has been stated that the temporal aspect of SS is two-fold, being that the onset of SS is positively correlated with the exposure duration of VEs during a single run and that repeated exposure to VEs can cause the onset of SS symptoms to decrease [36]. [19] goes more into depth with respect to these identified temporal aspects.

How can simulator sickness be mitigated? [54] looked into mitigating SS in a first person view VR broomstick simulation by means of multi-modal feedback in the form of wind and vibrotactile feedback, self-representation of the human body and the addition of gaze-vignette. First person view and gaze-vignette increased SS. However, wind and vibrotactile feedback decreased heartrate, inducing a calming effect on the user.

[34] argued that, taken the SCT, if VR users experience minimal vibrotactile feedback at the feet in a simulated car driving experience, sensory mismatch between real-world expected stimuli should decrease and therefore the onset of SS symptoms should lessen. SSQs were taken mid-test using a Microsoft Surface Dial, as opposed to after the trials, which is standard within research [47]. The test were conducted using an off-road simulator in VR and participants were placed on a vibrating platform. Results based on galvanic skin response, pupil size, heart rate, self-rated levels of discomfort and an SSQ indicated that the 11 participants with haptic feedback from floor vibrations showed significantly reduced measures of SS as compared to 11 participants without said vibrations.

[57] conducted a 240-person study, wherein participants were exposed to a 9 minute long walking video either with or without vibrotactile, visual and audio feedback. 8 different conditions were studied. Results indicated that vibrotactile feedback synchronized with an users' gait reduced SS and increased immersiveness.

[72] looked into synchronizing engine sounds and vibrations, coupled with

the visual perception of speed in a motorcycle simulator. Results indicated that the addition of synchronized engine sound and vibration reduces SS.

[86] looked at the use of bone-conducted vibration at the mastoid processes, a bony projection on either side of the temporal bone, in order to mitigate SS. Bone-conducted vibration is a technique that evokes a similar oculomotor and myogenic response compared to that of the otholith organs as a response to linear accelerations. Results from an experiment conducted in a cave automatic VE and using a HMD indicated a small effect in reducing SS. Precise placement of bone-conducted vibration devices might prove that the technique will not have sufficient appeal for individual commercial use. However, future work is required to look into possible benefits for utilizing the technique in a simulator training scenario.

4 Discussion

The main categories, some noteworthy current applications of haptics, and current research with respect to haptics in the aviation industry have been discussed. In this section, interesting possibilities for the application of haptics within the aviation scenario and the current challenges thereof are discussed.

A larger focus on the implementation of each of the different categories of haptics within the context of aviation simulation and training applications is given. Reasoning for this is two-fold. Firstly, a lot of research exists towards the use of haptics for i.e. enhancing immersiveness in VEs. Secondly, there has been an increase of interest for utilizing XR in simulated training scenarios. The combination of both of these trends makes it a natural choice to look at the utility of haptics for training and simulation purposes within the aviation industry.

Telehaptics and Haptic Shared Control in Aviation Some haptics implementations exist within aviation. Tele-haptics and HSC not much so [83].

An example of a teleoperation scenario within aviation that can utilize telehaptics or HSC is mid-air refuelling. Mid-air refuelling employs two techniques, one of which is the flying boom. A large fuel boom is manually controlled to refuel defence aircraft mid-flight.

As aircraft need to be flying in a certain envelope to engage with the flying boom, a variation of envelope protection using haptic feedback as proposed by [84] might prove as a beneficial addition for improving safety for both boom operator and aircraft pilot. Haptic shared control could be implemented to improve tracking performance. Vibrotactile feedback could also be used to convey the boom movement to increase immersiveness and transparancy. The same can be argumented for a simulated training variant of the task above. As training for mid-air refueling tasks with a flying broom is costly if done in real life, a simulated training protocol using e.g. XR and a similar implementation of haptics discussed prior, might prove to be a cost-efficient alternative for effective pilot training. More research needs to be done in order to find out how exactly

this type of haptic implementation should be realised technically. Such an implementation should be experimentally validated and the possible benefits and downsides thereof should be identified.

Surface Haptics in Aviation As aircraft become more advanced, cockpits and their interfaces do so as well. Steadily coming to replace mechanical buttons within real and training cockpits, digital flight displays can be provided with high quality tactile feedback. A technological challenge lies in the fidelity or resolution of the vibrotactile feedback opposed to mechnical buttons, sliders, and switches. As identified in [71] operation of mechanical controls involves kinaesthetic-cutaneous feedback, whereas digital screens can only provide the former as of current. A challenge lies in the addition of kinaesthetic or force feedback of digitally simulated mechanical controls to improve the fidelity thereof.

Haptic Wearables & Mid-Air Haptics in Aviation With the adoption of MR technology within current aircraft cockpits such as the F-35, haptic wearables and mid-air haptics might prove beneficiary for providing tactile feedback when manipulating virtual content. Similarly so for XR simulation training.

Cutaneous and kinaesthetic feedback can also induce self-motion to increase immersiveness and alleviate CS symptoms while remaining physically static. Not mature enough to fully substitute physical motion, future research can possibly achieve substitution of motion-based simulators in due time.

Downsides to haptic wearables is their intrusiveness and size. Body parts are (partly) obstructed, hindering physical interaction with real-life objects. Additional weight increases discomfort during long exposure operations. If purely digital content is used, these downsides can be overlooked. In that case haptic wearables might prove beneficial for improving immersiveness in VE interaction. Advancement in wearables becoming more light-weight and unobstructive, demonstrated in [81], will improve potential for use in AR and MR applications.

MaH can only convey cutaneous feedback. Future research needs to be conducted to find whether MaH can provide kinaesthetic feedback as well, considering the sense of touch requires both. The addition thereof will improve haptic feedback fidelity. Communication devices can pick up interference from the used ultrasone transducers, rendering it as an obstruction. Currently MaH is not yet feasible for use in a real cockpit, unless interference issues are solved. Also argued by [22], MaH is more feasible for use in simulation and training. Also true for haptic wearables, MaH still has to be actively improved and researched before actual use can be justified.

Multi-Modal Haptics in Aviation Real-life interaction uses multi-modal sensory input. Immersiveness within VEs will arguably increase when more modalities are accounted for. Multi-modal haptics could be utilized in simulation training for e.g. piloting and maintenance tasks. Immersiveness increases while SS decreases with the addition of more sensory feedback from VEs. An

example would be to provide thermal feedback when utilizing power tools that warm up due to friction. Another example would be to use wind to render a realistic sensation of aircraft velocity, combined with synchronized engine vibration as proposed by [72] to mitigate SS and improve flight simulation exposure time. More research on what combination of modalities provide what types of benefits as well as the how to successfully integrate these to work in conjunction with each other effectively requires more research.

5 Future Work

Research and application of haptics within aviation is limited. Multiple research opportunities exists. Focussing on the use of haptics for training and simulation applications within aviation, future work is suggested within this section.

5.1 Mitigating Simulator Sickness using Haptics

SS persists to be a challenge hindering training in simulation. [34] found that minimal vibrotactile feedback at the feet during virtual driving reduces the onset of SS symptoms, as it reduces sensory mismatch to a certain extent. [57] found that the addition of synchronized haptic feedback within a VR HMD has significant effect on the reduction of SS and improves realism in virtual walking. [72] shows that synchronized auditory and vibrotactile cues simulating an engine reduce SS symptoms. Given these findings, vibrotactile feedback associated with expected real life perturbations within statically set-up VEs should alleviate the onset of SS symptoms to a certain degree.

To confirm this hypothesis the effect of the level of fidelity and synchronization of simulated expected vibrotactile cues within VEs on the reduction on the onset, propagation and decay of SS syptoms could be researched.

An example research set-up can include a haptic vest, or vibrotactile feedback in the pilot seat which mimicks aircraft vibrations in simulated flight. To look at the effect of different levels of fidelity and synchronization on SS, variations thereof can be researched by e.g. introducing phase, amplitude, intensity, or localization differences.

The goals is then to facilitate longer simulation exposure times per training run as an effect of alleviating or mitigating SS.

5.2 Leveraging Self-motion

Haptic feedback can induce a sense of self-motion in XR and alleviate SS [57][13]. From [68], [67] and [69] it is found that humans can experience immersive flight using a VR HMD and a haptic suit. Given this research, the question arises as to how and to what extent one can approximate full physical flight in a static XR simulator set-up by using haptics to both induce self-motion and engine vibrations.

To answer this question, an example research set-up can include the use of a

haptic vest to generate engine vibrations, similar to [72], and a XR HMD with kinaesthetic feedback to induce self-motion, as done by[13]. Using COTS flight controllers to control a simulated aircraft in conjunction therewith, this relatively low-cost flight simulator set-up can be used to research simultaneously increasing exposure time, immersiveness and alleviating SS within simulated flight training.

5.3 Haptic Aviation Maintenance

Mainentance engineering requires motorskills obtained via rigorous training. The necessary tools and to-be-maintained equipment are both costly. Simulations can be considered a cost-effective training alternative. Both kinaesthetic and cutaneous feedback are important when handling machinery and tools, which some haptic gloves can provide. Thus, it can be asked to what extent one can effectively utilize kinaesthetic-cutaneous feedback enabled haptic gloves for handling digital maintenance tools for fine motorskill training within virtual aircraft maintenance engineering training protocols.

A limited amount of research is currently available that validates said question. Some research utilize a combination of VEs with physical tools instead [24]. To answer the research question, an example set-up can consist of a COTS haptic glove within an XR environment to perform a similar experiment as [11] who used a haptic teleoperation controller for simulated aircraft panel drilling. This allows a comparison to be drawn between haptic wearables versus teleoperation controllers.

Digital twins could be used to train maintenance procedures on virtual versions of their exact real counterparts [32]. This could facilitate more specific training protocols with respect to the required maintenance intervention. With the recent introduction of Neural Radiance Fields [48], a method for creating 3D representations using a sparse input of images, interest for the use of quickly producable digital twins within aviation maintenance engineering has gained traction as a reference tool [20]. Given this trend the prior research question can be extended to look into the physical interaction with digital twins for aviation maintenance purposes, and to ask what perceived benefits of utilizing haptic wearable gloves for the interaction with digital twins intended for XR based aircraft maintenance solutions are. An example set-up could revolve around the comparison between maintenance training using a general digital model versus on a digital twin, either with or without haptics, and how this translates to task performance on the maintenance procedure with its exact real counterpart.

6 Conclusion

This work summarizes the current state-of-the-art of haptics within aviation. Haptics are interesting for researching improvement of performance in piloting and maintenance tasks, immersiveness, and exposure time within simulation training. Main current challenges of training and simulation utilizing XR includes the onset of simulator sickness, correlating short exposure times to VR and

a need for a larger degree of immersivenes. Future work is suggested to look into 1) simulating and synchronizing expected real life perturbations via haptic wearables within flight simulation to decrease simulator sickness 2) leveraging self-motion for simulating a sense of physical flight using a static simulator set-up 3) utilizing haptic wearables for physical interaction of aircraft parts digital twins for improving extended reality based maintenance engineering performance.

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