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Recreational Motion Simulation: A New Frontier for Virtual Worlds Research

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Abstract

Motion simulation is a developing field which continues to grow with the recent incline in commercial virtual reality. Whilst the majority of motion simulation research focuses on flight simulation and training, its utility in recreational settings is often overlooked. Despite this lack of research, the use of motion simulators for recreational purposes spans decades, and is still today one of the most popular applications of motion simulator devices. Furthermore, with the recent development of low-cost motion simulation platforms, consumers have begun to use these devices in the home. Research regarding motion simulation and its effects in recreational experiences is needed now more than ever, and in this position paper we outline several reasons for its importance.

CCS Concepts
• ***Software and its engineering*** → ***Virtual worlds software;*** • ***Computing methodologies*** → ***Modeling and simulation;*** • ***General and reference*** → *General literature;*

1. Introduction

Virtual reality (VR) devices have advanced considerably in recent years, with VR finding utility in both industry and academia. In industry, VR has been applied to a broad range of disciplines such as training [HG20], video games [PPM19] and even theme park rides [JtDR*18]. As the popularity of VR technology continues to grow, so does its prospects for commercial entities; with a predicted compound annual growth rate of 18% from 2021 to 2028 [GVR20]. Virtual reality is also a well-established research domain with thousands of articles available in the literature. One research topic which has persisted since the birth of VR regards the effects it has on users, and how virtual experiences influence user behaviour. An interesting cross-section of this considers alternative sensory feedback devices and their effects on users.

A popular domain within this section of research considers motion simulation, specifically the addition of vestibular feedback in VR. Despite the volume of research in motion simulation, there is almost no research into recreational uses. This is especially jarring given the number of VR video games which support motion simulation software output, and the popularity of simulation video games such as *Assetto Corsa* or *Flight Simulator X*.

In this position paper we highlight the clear need for further research into motion simulation and its use in recreational settings. This is achieved by outlining evidence which demonstrates the urgency for investigation in this area, and the potential benefits it may bring to both academia and the commercial sector. Key elements of these domains are explored, in which the development of interest for virtual reality and motion simulation is considered. Finally, areas of future work are delineated, which contribute to building a strong foundation for this under-researched field.

2. Growth in the Commercial Sector

Motion simulation, as a technology, was established in the later half of the 20th century. Initially developed for its application in entertainment, it soon found utility in providing realistic training experiences to pilots. Despite its early inception, it still finds considerable utility today; with applications flight simulation [Sch99] and machinery operation [KEKT11], to name a few. The aviation industry realised the potential of motion simulation in training pilots for realistic flight scenarios. This led to the development of motion-driven flight simulators. The earliest example is the Link Trainer, a rudimentary flight simulator patented by Edwin Link in 1931 [Lin31]. The Link Trainer used electrically-driven pumps and rudder pedals to move the cabin, and provide simulated motion. An example of a Link Trainer can been seen in Figure 1.

Today, flight simulation is still a large industry and continues to grow. Many of today's modern flight simulators feature moving-bases powered by motion simulation to provide users with a range of realistic vestibular cues. Flight simulation has remained one of the most popular applications of motion simulation inside the commercial sector, with a predicted compound annual growth rate of 5.2% to 2025 [MM20]. With an increasing growth of the flight

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Figure 1: *An example image of Link's trainer, one of the first moving-base flight simulators.*

simulator market, comes a demand for motion simulation technology to drive moving-base flight simulators. This is just one aspect which highlights a rapid growth of motion simulation hardware in the coming years.

Whilst the emphasis of motion simulator usage is in flight simulation and training, another area in which it is finds significant utility is in recreational settings. To name just one example, Disney's Star Tours attraction used a refurbished military flight motion simulator to provide ranges of motion to customers, and enable a recreational experience of space-flight [PSPS18]. Disney's Mission: SPACE is a more recent example of a motion simulator ride, adopting a centrifugal approach to actuate motion for its riders [JPG*09]. As theme parks continue to grow, with an expected $56.5 billion consumer expenditure in 2021, the demand for motion simulator attractions may also subsequently increase [LVLL20]. This is supported by the fact that new and diverse vacation experiences are a driving factor of theme park growth [Mil01]. To the prospecting park developer, motion simulators are an attractive option to offer recreational experiences whilst maximising profits; simulators can accommodate thousands of customers per hour, a much higher attraction capacity than most other rides [Het94]. As such, the interest in motion simulation could increase, highlighting once again, an increase of motion simulation interest and development.

The utility of simulating motion is not limited to amusement rides, however, and spans many other recreational applications. For example, motion simulation is a key feature of "4D theatres", where sensory feedback is expanded to include cues outside visual-auditory information. Unlike a regular cinema, these theatres stimulate additional sensory modalities to enhance the experience of the viewer, with motion feedback being a tool often used for this purpose [LHC15]. Motion feedback is also an often-utilised aspect of arcade attractions, and has been used for many years. To illustrate this, Cohen outlines many early examples of arcade games which feature motion feedback as part of the experience [Coh03]. Despite their early adoption of simulated motion, arcade attractions still often utilise motion feedback as part of the recreational experience today [LE15]. Motion feedback can be used in combination with video games to emulate experiences similar to that of an arcade or theme park, but within the home. An example of this is the recent popularity of 'SimPits'; amateur simulation platforms designed with video games or simulation software in mind [SS10]. With the advent of cheaper hardware and the recent boom in virtual reality, motion simulators have generally declined in price recently. This has not only driven interest to these devices, but also made their purchase more viable to the consumer [Mil18]. As a result, there are several low-cost motion simulators currently available on the market. Two examples can be seen in Figure 2.

Figure 2: *Image of Yaw VR (left) and DOF Reality 2-DoF Seat Mover MS2 (right), two low-cost motion simulators. As of June 2021, these are priced $1,490 and $749, respectively.*

The increasing attainability of these devices, coupled with an growing desire by consumers to purchase motion simulators as recreational devices [Chi12], points towards a future increase of interest and development in this field. There have already been several patents for motion simulator designs specifically targeting personal recreation [Chi12, KAGB01], and a recent emphasis on low-cost motion simulator prototypes in the literature [Mil18]. When seen together, this evidence reveals a growing desire by consumers to purchase and use motion simulators within the home. The demand for cheaper, more attainable motion simulators will likely drive the commercial sector to increasingly supply viable solutions. Motion simulation as technology may, after some period, be a typical device found in the home of the average gamer. More attainable simulators will also provide easier access to institutions for research purposes, potentially offering a boom in motion simulation research alongside its growth in the commercial sector.

3. Gaps in the Literature

One issue with the majority of motion simulator research is the differences of simulator architecture between studies. Simulators throughout studies can range from simple two-degree of freedom simulators [ZSC14] to high-fidelity multi-axis motion simulators such as the MPI CyberMotion simulator, seen in Figure 3. Motion simulators can differ in many ways; they can provide different degrees of movement, angular limits, and so forth. It has been shown in previous work that differing degrees of motion fidelity can considerably affect the outcomes of experiments [ZSC14], posing a problem comparing cross-study results. This raises an issue for both researchers and developers alike, as effects observed in these studies may only be pertinent for that specific set-up. On a similar note, motion cueing algorithms are often tweaked to the subjective opinions of experts, further obfuscating cross-study validation [HA16]. These issues not only hinder the progress of motion simulation research, but also its adoption. There have been attempts to provide objective testing of motion simulators, but these are limited to specific contexts. For example, the OMCT (Objective Motion Cueing Test) [SvPM*13] provides a normalised scoring system for motion fidelity, but is only relevant to flight simulator software and hardware. Ideally, a objective method in analysing motion simulation, regardless of simulator architecture, is required to counter these problems and accelerate the development of this field.

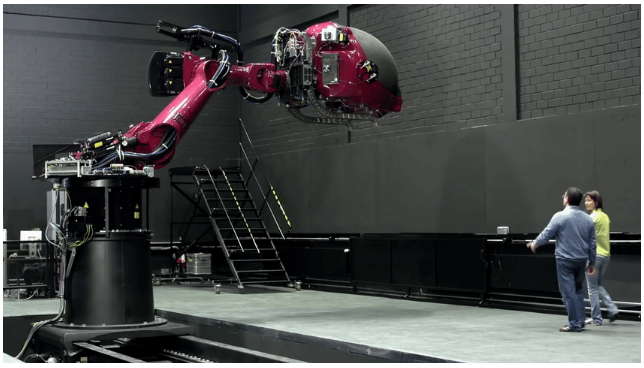

Figure 3: *The MPI CyberMotion simulator, a 6-DoF motion simulator, actuated by a robotic arm.*

Motion simulation is not limited to applications within training or task performance, however. Utilising motion simulators in a recreational sense, for example, in video games, is another popular use. Simulation games have been previously considered in the literature, specifically for their use as learning tools [ORGS15]. However, there are very few papers featuring video games in the context of motion simulation. It could be the case for example, that user behaviour differs in recreational settings, as opposed to more serious use cases. For this reason, it is worth understanding how motion simulation may impact game experiences, in contrast to its use in training. As mentioned previously, the advent of affordable motion simulators has led to a rise in the market, and popularity amongst gamers. Despite this newfound interest, the literature lags behind, with comparatively little research involving motion simulation and games. With that being said, there has been a handful of initial research involving motion simulation and its use in video games. However, the majority of this research describes the application of simulation for learning purposes, but fails to study the effects of motion [HKE*09]. One of the only studies which considers how motion simulation affects video game players was by Proctor et al. [PBL07], who found that the presence or absence of motion cues had no impact on in-game performance, or skill development of users. Although there are a small number of papers involving motion simulation and video games, it is still a significantly under-researched area. In addition, the impacts of motion simulation on player behaviour remains an unexplored area of research. Determining for example, if player behaviour is affected by motion simulation could not only be useful information to developers, but also foster the creation of novel motion-based game mechanics. It could also inform those building video games with motion platforms in mind of the player's experience and how it may be altered.

Understanding how technology impacts users is a common theme in Human-Computer Interaction (HCI) research, and aligns closely to this issue. Whilst HCI is a substantial field of research, examining motion simulation is an often overlooked subtopic. Despite this, some papers have considered motion simulation and its utility for HCI research and rapid experimentation [RRH19]. Considering some emerging challenges associated with VR, such as addiction and over-attachment to virtual agents, may be interesting to consider in the context of motion simulators [SSA*19]. For example, understanding how motion simulation alters a user's attachment to virtual environments could lead to some interesting insights. Another consideration for research focusing on motion simulation is its lack of a formal definition. Currently, no framework or classification exists to categorise what is and is not motion simulation. The creation of such a classification model would establish what constitutes a motion simulator, and help research into understanding cross-simulator effects.

4. Implications for Cybersickness

Following on from the topic of VR games, a common side-effect afflicting virtual reality users is cybersickness. Cybersickness is a form of visually-induced sickness often felt by those using virtual reality devices. It is often compared to motion sickness, with a similar range of symptoms, but fundamentally separate conditions [SKD97]. This is in part due to the differences regarding how they are induced, with cybersickness capable of being induced solely from visual movement, unlike motion sickness [LJ00]. The illusion of motion in this manner, being visually induced rather than induced by actual motion, is commonly known as 'vection'. Whilst there have been several theories surrounding its pathology such as the postural instability theory [SSJ98] or poison theory [LJ00], the most prominent surrounds conflicting sensory information. The theory suggests that cybersickness is brought about by the disparity between sensory inputs, specifically a mismatch in the visuo-vestibular system [LJ00]. Specifically, sickness arises when visually perceived motion does not align with information from the vestibular system.

Cybersickness can present itself quickly to users of virtual reality, posing a considerable issue in its use. It is clear that cybersickness is a considerable usability issue, which not only hinders the adoption of virtual reality, but also limits the range of interaction in VR. This issue has driven the exploration of methods to mitigate the severity of cybersickness. As a result, there has been several successful experiments in this area, for example, using airflow to reduce symptom severity [HH*19]. Many other methods of combating cybersickness in recreation have been seen in previous research, such as using specific movement modalities [ACH18] or using foveated blurring techniques [HCS21].

With this in mind, there is a clear motivation behind studying the impact of motion on user sickness. The sensory conflict theory, as mentioned previously, concerns a mismatch between the visual and vestibular senses. Regarding this theory, VR sickness could be due to vection (provided by the headset), in the absence of congruent vestibular information. In theory, the inclusion of vestibular cues, synchronised to the visual display via a motion simulator could eliminate the conflicting relationship. If this is the case, it could be argued that cybersickness should not be present in this scenario. However, investigation would be needed to examine if this also elicits the onset of motion sickness instead. Futhermore, the postural instability theory hypothesises the cause of cybersickness to be due to unfamiliar circumstances presented to the user. In virtual reality, it may also be the case that scenarios involving vection with the absence of physical movement are atypical of movement in the real world. Considering this, the use of motion simulation could resolve the problem by providing a vestibular cues similar to those of a life-like experience of movement. This may also increase player presence, which has been shown to reduce cybersickness [ZWB*17]. Motion simulators have also been shown to substantially increase user presence [KRH*18], lending further credit to this being the case.

In each of these cases, whether considering the resolution of the incongruent visuo-vestibular relationship, providing an experience closer to the real world, or increasing user presence; it can be seen that motion simulation could be a useful method of mitigating cybersickness. There is a strong motivation for investigation in this domain, and as a result, several studies have been published with this in mind. Despite theories suggesting motion sickness improvement, previous evaluations comparing motion/no-motion settings show mixed results [HBK*90]. A later study addresses this by testing a range of feedback conditions, rather than the presence/absence of motion. However, the results show no motion had significant effect on user sickness [KRH*18]. Interestingly, another similar experiment found the opposite, finding that combined visual-vestibular feedback decreased subjective cybersickness scores [NCL18]. Perhaps one explanation for this disparity is the difference in virtual environment. For example, low-visibility of the environment has been shown to increase sickness severity in the case of motion simulation [DBBT14]. It could also be the case that results cannot be compared between the two due to differences in simulator architecture.

The mixed results found in the literature not only show the need for a suitable experimental methodology, but also the opportunity for further research. Cybersickness is a considerable issue in virtual reality applications, posing issues for its adoption and development. Although there is a handful of papers concerning cybersickness, the area of utilising motion simulation to mitigate its effects could benefit from more attention. Understanding this topic in more detailed could, amongst other things, be beneficial to players and developers of VR games; especially in the context of recreational motion simulation.

5. Visually Congruent Feedback

Whilst these studies test conditions with or without motion, the congruence of feedback is not considered in detail. The majority of experiments in this domain concern synchronised visual and motion feedback throughout. Conversely, some authors have tested a range of scenarios with a motion simulator, finding incongruent motion cues inconsistent with the visual feedback to be the most sickness-inducing condition [BMP05]. The findings could suggest the presence/absence of cues does not affect sickness as much as large differences between them, when both visual and vestibular cues are present. This could not only have benefits in mitigating cybersickness, but spreading interest for motion simulator technology.

Although there has been a handful of papers focusing on the congruence of the visual and haptic senses in VR, there is little to none which consider this in a motion simulation setting. Furthermore, prior studies largely evaluate effects only in the presence of induced visuo-haptic feedback. In our previous work, we addressed this gap in the literature by performing an investigation of visuo-haptic feedback congruency in a motion-base setting [WGH20]. Our findings show no significant differences between congruent/incongruent visuo-haptic feedback groups, counter to previous literature. Interestingly however, participants were more able to evaluate their own performance in the case of congruent visuo-haptic feedback. The results show that ultimately, a simulated motion environment can affect the visuo-haptic integration process through the introduction of induced vestibular cues.

It may be the case for example, that similar effects are seen with the visual and vestibular sensory relationship. For example, the introduction of inversely-correlated visuo-vestibular cues could have an unexpected effect on user presence, or cybersickness. On that note, given that virtual reality games are inherently multisensory, the lack of research in this area is surprising. Exploring how congruent and incongruent visuo-vestibular information affects users of VR could lead to methods of mitigating cybersickness, or creating more enjoyable recreational experiences. This is especially important considering the often conflicting sensory information commonly found in VR applications [BKC01]. This is certainly an area of research which requires further attention, and would greatly benefit the world of recreational motion simulation.

6. Current Research

To address this, we are currently investigating how visuo-vestibular congruency affects the users of virtual reality experiences. We are specifically interested in how motion which is either correlated or inversely-correlated to visual feedback, can affect:

1. Player behaviour and performance within virtual reality;
2. Measures of sickness, or;
3. Measures of user presence.

To conduct this research, we test three groups using a within-subjects methodology and a motion simulator. These groups consist of a no-motion control, and two groups with differing visuo-vestibular feedback; in one, visuo-vestibular feedback is correlated, and the other, is inversely-correlated. Participants are tasked with playing a virtual reality driving game, in which they are asked to complete two laps as quickly as possible. The game used is Project CARS 2, a popular racing simulator game.

Participants are subjected to three sessions in total across a period of two weeks, in which they experience all three motion conditions. The order in which motion conditions is selected randomly to control against order effects. Following each session, subjective measures of cybersickness and user presence are recorded for the participant. We utilise Witmer and Singer's Presence Questionnaire (PQ) [WS98] and Simulator Simulator Questionnaire (SSQ) [KLBL93] to measure these metrics. Furthermore, detailed telemetry and in-game data is recorded to gauge how the motion conditions affected driving style, performance and other aspects of the experience. We intend to utilise this methodology to examine the differences of each measure, in the presence of the three motion conditions. This will enable us to determine some of the effects motion congruency has on player experiences in virtual reality, specifically its impact on measures of sickness and presence. Furthermore, player performance metrics and in-game telemetry data will allow for the investigation of the effects of motion congruency on player behaviour.

Our initial results show promise that participant sickness can be reduced through repeated exposure to Virtual Reality. Secondly, correlated visuo-vestibular feedback appears to slight reduce sickness initially, whereas inversely-correlated motion greatly increases measures of sickness in the first session. However, this is not observed in later sessions. Regarding presence, subjective ratings of participant presence did not dramatically decrease across the three sessions, with only negligible differences being observed. Furthermore, our initial results suggest inversely-correlated feedback resulted in significantly lower measures of presence than other conditions. Supporting this observation, the correlated feedback group elicited the highest ratings of participant presence. Finally, motion conditions did not greatly affect player performance, but did have an effect on training effectiveness. However, these observations are founded in a partial analysis on a work-in-progress study. With that being said, we are encouraged that further research is warranted.

7. Opportunities for Future Work

Considering the need for research into this topic, there are many opportunities for future work. These could, for example, include the investigation of how the presence/absence of motion affects factors like cybersickness, presence, or even game enjoyability. In addition, the novel use of motion simulation as a game mechanic could lead to an interesting avenue of research. Investigating the impact of sensory feedback types within the context of motion simulation could also be beneficial in this field. Typically, low-cost simulators also include other feedback devices such as vibrotactile transducers, airflow devices, or even haptic resistance gloves. Another interesting method which could be employed alongside motion simulation is galvanic vestibular stimulation, in which the body's sense of balance is affected directly through simulation rather than physical motion cues. This could offer some promising future work, and certainly requires further investigation to assess its utility for simulating a feeling of motion. Another interesting direction to expand work into would be the standardisation of testing across simulator types. Investigating, for example, the difference in player experience between three and four degree-of-freedom simulators could show how distinct ranges of motion affect players. Finally, exploring the congruency of sensory information in detail, and how it affects players, would also be a useful contribution to this field.

8. Conclusion

In this position paper we have presented several arguments to justify further research into the often overlooked field of recreational motion simulation. Motion simulators are used throughout recreational attractions such as theme parks, arcades and video games. With the advent of low-cost simulators just hitting the market, consumers are beginning to purchase simulator setups for video games at home. Despite this, the literature does not reflect the recent surge in popularity of motion simulators in recreation. Currently, articles focusing on recreational motion simulation are few and far between, with the effects of motion simulation on games largely unknown. Furthermore, simulator architectures between studies differ largely between experiments, making results hard to examine. Some researchers do investigate virtual reality and motion, but there has yet to be any articles which concern how motion simulation affects a player's behaviour in-game.

On the topic of virtual reality, a prominent issue afflicting users is that of cybersickness. The leading theory surrounding its pathology hypothesises that conflicting visuo-vestibular information is the reason for its manifestation. One potential method to reduce cybersickness is the utilisation of motion simulation to remove the conflicting visuo-vestibular senses. However, work in this area contains many mixed results and further research is required to ascertain how motion simulators affect sickness measures. By the same token, virtual reality is an inherently multisensory experience for its users, who integrate a diverse range of sensory information. Two of these are the visual and vestibular senses, which not only play a part in types of motion sickness, but also the experience itself. Taking all of this into account, it is clear that further research into recreational uses of motion simulation is needed. As outlined in this paper, there are several factors which highlight the urgency for further work. For this reason, and the many others discussed, the field of recreational motion simulation could benefit from more attention.

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