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Comparing Virtual Environments for Cybersickness Using a Cumulative Optical Flow Entropy Metric

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ABSTRACT Cybersickness, or feelings of nausea, discomfort or unease, are common in virtual reality experiences with head-mounted displays. With the widespread availability of virtual reality headsets across a wide domain of uses including industry, defence, education and the commercial market, is it critical that virtual environments are developed that minimise cybersickness. Unfortunately, determining whether a virtual reality experience will induce cybersickness is difficult. Typically this requires user studies with a completed, or almost completed, virtual environment. This is time consuming and expensive, both to run participant-based user studies and for any rework to the virtual environment needed due to identified issues. As part of modern iterative development processes it would be useful to pre-evaluate virtual environments for cybersickness before engaging user studies. This paper presents a new approach and metric to compare virtual environments' susceptibility to induce cybersickness. The approach combines visual optical flow, an entropy metric of complexity and a cumulative time-series measure. Virtual environments with known cybersickness attributes are used to demonstrate the approach. Results indicate that the approach can successfully differentiate between known levels of cybersickness and attributes contributing to cybersickness, such as motion direction and field of view.

INDEX TERMS Virtual reality, cybersickness, head-mounted display, optical flow, field of view.

I. INTRODUCTION

The widespread availability of affordable head-mounted displays and easy access to virtual reality (VR) applications and games has significantly increased the use of such technology by the general public. However, a significant portion of the population suffer negative effects from VR technology use, commonly referred to as cybersickness [1]. This can happen in situ and linger post usage. Cybersickness is associated with feelings of illness, discomfort, dizziness and unease [2]. Poor virtual reality experiences involving cybersickness can deter users from the future use of such technologies [3]. Therefore considering and designing to eliminate or reduce cybersickness in VR software is crucial [4, p507].

Determining cybersickness typically requires participant-based user studies. This often requires large numbers of participants as cybersickness is a subjective experience. Also measurement is difficult as it is either intrusive (for example attaching physiological biometrics devices [5], [6] or use of concurrent verbal protocols [7]) or relies on post-session recollection (for example use of questionnaires, i.e. simulation sickness questionnaire (SSQ) [8] or the motion sickness assessment questionnaire (MSAQ) [9]).

An alternative approach is to objectively distinguish visual features that are indicative of generating cybersickness events. There has been considerable research looking at optical flow within virtual reality experiences [10], [11]. Optical flow is an approximation measure that analyses motion changes between image frames in a time sequence to characterise visual motion [12]. However, there are a number of issues with using optical flow measures as indicative of cybersickness-inducing environments. Firstly, optical flow events are characterised with horizontal flow, vertical flow and magnitude components and they each contribute differently to visual impact. As these components are experienced by users concurrently, there is only limited insight that can be gained by independent measurement [13]. Secondly, the number of optical flow events can significantly vary between virtual environment sequences, for example based on the movement rate and elements in the environment. Optical flow measures may indicate that environments are different, but the number of optical flow events may not necessarily be indicative of positive or negative user experience. Thirdly, optical flows are typically generated across

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sequential frames, in visual motion streams or from video capture, and it is unclear how regularity or complexity of these time series contribute to cybersickness-inducing experiences. Finally, all optical events are not equal contributors to motion/cybersickness sensitivity, for example differences in visual events across focused and peripheral vision areas can impact cybersickness [3], [14]. Considering where the optical flow events appear, in the visual field of view, is likely to be significant.

In the work described here, a new approach is proposed to objectively characterise self-motion experiences in head-mounted display (HMD)-based virtual environments. The aim is to determine cybersickness inducing features as part of an iterative development process to allow prototype virtual environments, or different versions of the same virtual environment, to be compared and improved before progressing to user studies. The approach combines optical flow metrics and an entropy complexity measure across focused and peripheral field of view components to distinguish between virtual environments.

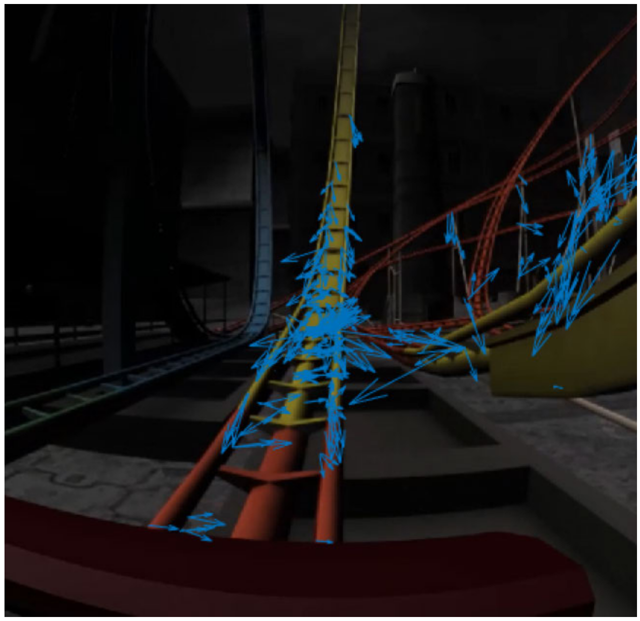

FIGURE 1. Optical flow events, scaled and visualised, to show motion magnitude vectors in the Parrot virtual roller-coaster (NB. optical flow scale factor = 200).

II. RELATED WORK

A. CYBERSICKNESS

Cybersickness as a result of head-mounted display use has been an ongoing research topic (recent reviews include [1], [15], [16]). Cybersickness is a noted side-affect associated with exposure to simulated environments, and in particular, exposure through VR HMDs [1], [6], [17]. Typical symptoms of cybersickness include nausea, eye-strain and dizziness [18].

Symptoms are known to vary greatly between individuals, and depend on the technologies being used, the design of the environment, and the tasks users are performing in the environment [19]. Cybersickness also has a cumulative effect based on time spent within virtual environments [14], [20] and is positively impacted by reducing field of view, for example by blocking peripheral visual motion [3], [14]. Efforts to further understand and potentially negate susceptibility to simulation, motion, and cybersickness have led to the development of a variety of measurement approaches.

Most cybersickness research measures the effect by use of questionnaires, e.g. the simulator sickness questionnaire (SSQ) [8], postural instability [21], or biometric and physiological states [5], [6]. Topical work has also explored impacts on cognitive performance [2], [6], [7]. Although a number of robust measures have been developed [16], subjective measurements may be impacted by systematic biases and psychological factors [22].

B. OPTICAL FLOW

Optical flow is an approximation measure that defines image motion as a projection of 3D surface points onto a 2D image plane [12]. Through analysing changes between image frames in a time sequence, the structures of an optical flow field can be used to recover 3D motion and the motion of the original sensor. Optical flow is useful for numerous computer vision tasks including motion detection, object segmentation, time-to-collision and focus of expansion calculations, motion compensated encoding, and stereo disparity measurement [12]. An example of optical flow events can be seen in Fig. 1 where movement between two sequential frames in a virtual roller-coaster are represented by vectors with horizontal flow, vertical flow and magnitude components.

A detailed review of optical flow use is outside the scope of this paper, see for example [12], [23], [24]. However, the information represented by optical flow in a virtual environment provides insight into motion regularity and complexity [25]. For example, consider a virtual environment where high intensity motion is constantly generating high volumes of optical flow events. The intensity of the visual experience over time will likely impact the user experience. Smith, Blackmore and Nesbitt [13] noted that experiencing virtual environment motion with high regularity across high optical flow count and magnitude measures would indicate more intense visual motion, resulting in increased cybersickness. In order to capture this motion regularity, they explored the use of entropy metrics.

C. ENTROPY METRICS

Entropy metrics have a long history of use in characterising signals [26], [27], complexity [28], [29] and motion [30], [31]. For example, approximate entropy (ApEn) is a method used to provide a general understanding of the complexity of data [26], [29]. Chon, Scully and Lu [26] note that "ApEn determines the conditional probability of similarity between a chosen data segment of a given duration and the next set of segments of the same duration; the higher the probability the smaller the ApEn value, indicating less complexity of the data.''

In the context of applying entropy metrics to optical flow events, less complexity in entropy indicates more regularity in the data series and thus a more intense and consistent experience. For virtual environment analysis, lower entropy, i.e. complexity in a time-series of optical flow events, indicates higher regularity in the optical flow metrics. Smith, Blackmore and Nesbitt [13] found that ApEn could distinguish between different virtual environments. However, this work only considered the optical flow event count and magnitude. Information on motion direction was not used. The current approach extends this work by combining optical flow and entropy metrics with a cumulative time-series measure to characterise optical flow count, magnitude, and direction contributions, and cumulative impact.

III. CUMULATIVE ENTROPY MOTION VALUE

The approach described here has three main steps. Step 1 requires that a video of motion in the virtual environment to be evaluated is captured. Ideally this is directly from the HMD with a first person view of what a user would see during a session.

During Step 2 every frame of the video is processed in sequence with a number of sub-steps. Step 2a calculates the optical flow of the current frame. This generates a vector of magnitude and direction for each optical flow event. Step 2b then partitions each optical flow event by its direction to determine a regularity measure of motion in the frame. An entropy motion value (EMV) is calculated for each frame. A summary and relevant formulas for this calculation are summarised below, from [31]. Each optical flow event is sorted into one of 16 direction ''buckets'', evenly distributed across angles from 0 to 2π (noted as $AngNum = 16$). Let p_k be the optical flow vectors that are in the kth sub-angle, and the motion directivity entropy along the kth sub angle is

$$E_k = -p_k \cdot \log(p_k). \tag{1}$$

The magnitude of all the optical flow events, M_k that fall in a direction bucket is calculated with a weight factor by

$$M_k = \frac{Magnitude_k}{\sum_{k=1}^{AngNum} Magnitude_k}. \tag{2}$$

In Step 2c, using E_k and M_k, the entropy motion value (EMV) [31] of the frame is determined via the formula

$$EMV = \sum_{k=1}^{AngNum} M_k \cdot E_k. \tag{3}$$

The output from Step 2 is a time series of EMV data for frames in the video. During Step 3, the cumulative total of the EMV time series is calculated and plotted to provide the cumulative EMV (CEMV) profile. The CEMV profiles of different virtual environment motion can then be compared as described in the following case study. A summary of the three steps is shown in Fig. 2.

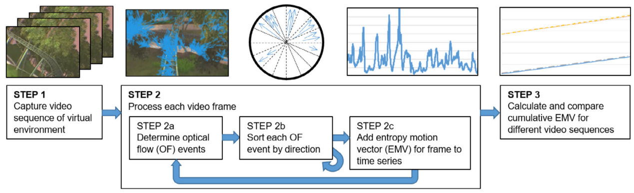

FIGURE 2. Overview of cumulative entropy motion value approach.

A. DATA COLLECTION

Optical flow data was captured from two virtual roller-coaster rides known to induce different levels of cybersickness. The Helix Coaster (ArchiVision, Wierden, Netherlands) and ParrotCoaster (Psychic Parrot Games, USA) virtual roller-coasters were used in cybersickness experiments [6], [7]. Nalivaiko *et al.* [6] found significant differences between the two virtual roller-coaster simulators in the extent of their nausea provoking capacities. Cybersickness was determined both with the time participants could spend in the experiences before developing nausea ($p=0.054$) and the average nausea rating ($p=0.000003$). In both cases the Helix roller-coaster was more likely to induce nausea symptoms [6]. Only two ($n=12$) of the participants who experienced the Parrot roller-coaster were required to stop while 8 ($n=12$) of the participants who experienced the Helix requested to stop before the allotted 14 minutes of ride time [6]. Nalivaiko *et al.* [6] observed that their study was not intended to identify cybersickness problems with the Oculus Rift specifically or VR technology in general. They deliberately chose a provocative roller-coaster experience to provide conditions that would invoke nausea.

In the work reported here, videos of virtual roller-coaster rides were captured using the same set-up as [6], namely from an Oculus Rift Development Kit 1 (DK1). The videos captured a stationary HMD stereo view of one complete loop of each ride. Videos were captured in both forward facing [6] and backward facing [5] positions, resulting in four videos namely, Helix forward facing, Helix backward facing, Parrot forward facing and Parrot backward facing.

Example video frames of the Parrot and Helix virtual roller-coaster rides can be seen in Figs. 3 and 4 respectively. Each video was captured as a MPEG-4AVC file at 1920×1080 resolution, 30 frames per second and a sample rate of 48000Hz.

MATLAB R2020a was used to process the videos. Optical flow metrics were calculated using *estimateFlow(opticFlow,I)* which estimates optical flow using the current image, I, and the previous images (accessed via the MATLAB function *VideoReader*). The standard MATLAB *opticalFlowLKDoG* class, that estimates optical flow using the Lucas-Kanade derivative of Gaussian method, was used. New MATLAB scripts were developed to calculate the EMV, based on [31] and specifically the formulas 1-3 in Section III.

The output from the MATLAB scripts is a time-series of EMV values representing the video frames. The EMV time-series of the four main videos was supplemented with

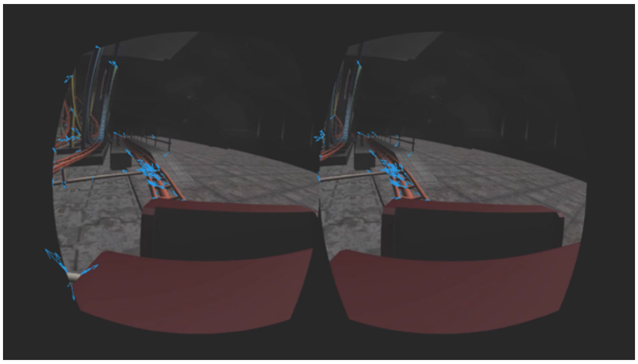

FIGURE 3. **Parrot roller-coaster backward view with optic flow events marked. (Optical flow shown with a 200 scale factor. All video processing was completed with grayscale images and without displaying the images or optical flow elements. Thus any color images are representative and not examples those actually processed.)**

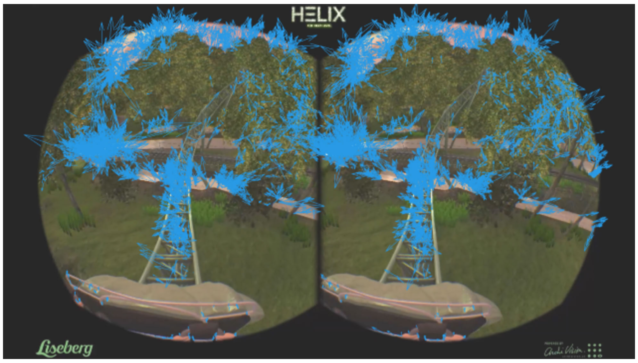

FIGURE 4. **Helix roller-coaster forward view with optic flow events marked. (Optical flow shown with a 200 scale factor.)**

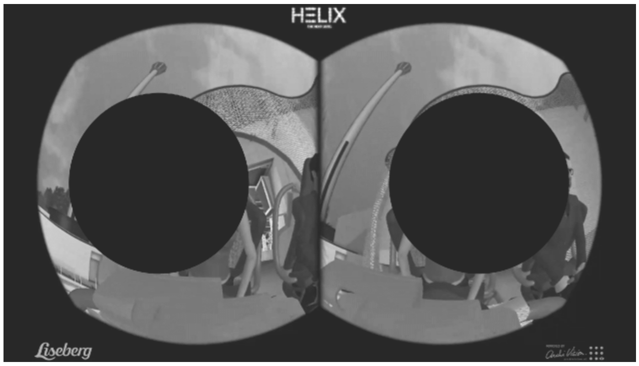

FIGURE 5. **Helix backward view for peripheral view data collection with focused overlay mask.**

FIGURE 6. **Parrot forward view for focused video data collection with peripheral overlay mask.**

EMV time-series where overlay masks were used to separate focused view and peripheral view components of the videos. Blocking greater than or showing less than 80% FOV [3] was used to generate the overlay masks. Examples of virtual roller-coaster views with overlay masks are shown in Figs. 5 and 6. Each overlay mask was the same size and applied to each side of the stereo display. Eight additional time-series were thus generated: Helix forward focused FOV, Helix forward peripheral FOV, Helix backward focused FOV, Helix backward peripheral FOV, Parrot forward focused FOV, Parrot forward peripheral FOV, Parrot backward focused FOV, and Parrot backward peripheral FOV.

The results from the 12 EMV time-series were processed in Microsoft Excel (Office365 edition) to generate the cumulative EMV (CEMV) data as presented in the Results section.

All computations were completed on an Alienware Aurora R5, Intel Core i7-6700K CPU @ 4.00GHz with 16GB RAM running 64-bit Windows 10.

B. HYPOTHESIS

Our hypothesis explores our new optical flow/entropy metric (CEMV) with two virtual reality roller-coasters with known differences in inducing cybersickness. We propose that the new metric will:

- H1: Differentiate between virtual environments with different cybersickness inducing-profiles. Specifically, the Helix roller-coaster is known to be more likely to induce cybersickness [6], [7] and will have a more regular, less chaotic, entropy profile than the Parrot roller-coaster [13].
- H2: Differentiate between different exposure stimulus in the same virtual environment. In this case, travelling backwards in the roller-coaster, or rear view, is better than facing the forward direction for inducing cybersickness [5].
- H3: Differentiate between field of view components that contribute to inducing cybersickness. For example, the distribution of peripheral view and focused view optical flow events provide insight into how to reduce cybersickness through restricting peripheral views [3], [14]. Thus, environments with lower cybersickness, i.e. the Parrot roller-coaster, should have a better metric profile across peripheral/focused view events than the Helix roller-coaster.

IV. RESULTS

The attributes of the roller-coaster videos captured from the Oculus Rift HMD are shown in Table 1. Each video depicted one complete loop of each roller-coaster, from a first-person perspective, with either a forward or backward facing position. When comparing the different roller-coaster

TABLE 1. Roller-coaster videos attributes.

Attribute	Helix Forward	Helix Backward	Parrot Forward	Parrot Backwards
Resolution	1920 x 1080	1920 x 1080	1920 x 1080	1920 x 1080
Frame rate	30fps	30fps	30fps	30fps
Duration	1:22	1:22	1:36	1:36
Frames processed	2468	2468	2898	2898
Last $\frac{1}{4}$ frames	617	617	725	725

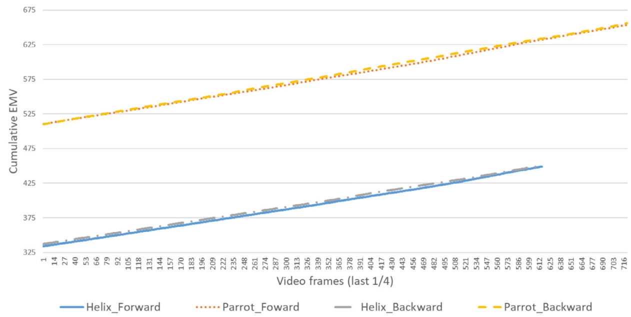

FIGURE 7. Cumulative entropy motion value (CEMV) for forward and backward motion in two roller-coasters.

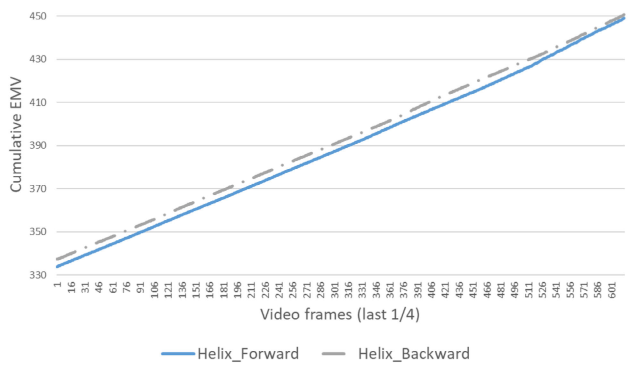

FIGURE 8. Cumulative entropy motion value (CEMV) for forward and backward motion in the Helix roller-coaster.

rides together, the results of all the frames processed are presented. However, when considering each ride individually, as a cumulative metric is being used, only results representing the end of the ride, in this case the last quarter of frames for each ride, are presented.

Entropy measures demonstrate the presence of regularity in signals. Lower values indicate more regularity, and in this case, increased cybersickness inducing visuals [13], [25]. As shown in Fig. 7, our cumulative metric has identified a similar pattern in the two roller-coasters. Both the forward and backwards motion metrics for the Parrot roller-coaster have more chaotic and less regular CEMV measures than the Helix roller-coaster.

Thus, H1 is demonstrated across both motion directions (Helix Forward versus Parrot Forward and Helix Backwards versus Parrot Backwards) for the two roller-coasters. However, due to the plot scale it is difficult to see the differences between forward and backward motion for each individual roller-coaster. Therefore, we have examined each ride individually.

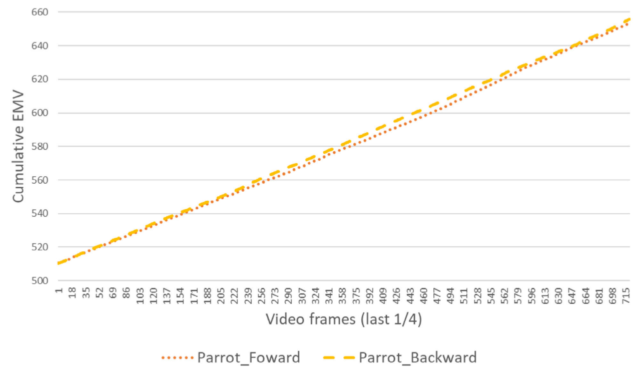

FIGURE 9. Cumulative entropy motion value (CEMV) for forward and backward motion in the Parrot roller-coaster.

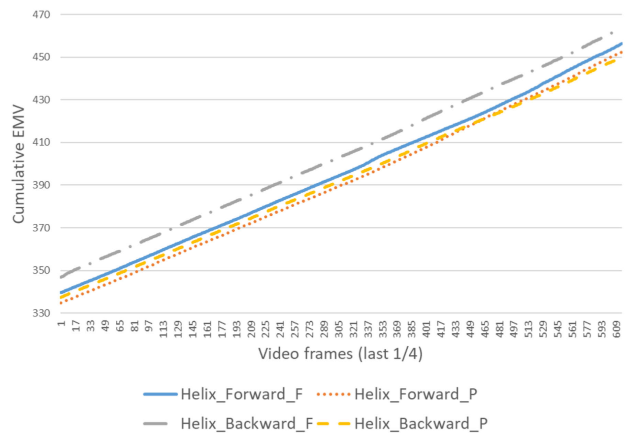

FIGURE 10. Cumulative entropy motion value (CEMV) profile for forward and backward motion across focused (_F) and peripheral (_P) field of views in the Helix roller-coaster.

Fig. 8 shows the cumulative EMV for the Helix roller-coaster for both forward and backward motion. Although the difference is minimal, the backward motion has a consistently higher value, implying less regularity. This concurs with [5] where backward motion in the Helix roller-coaster was shown to be less likely to induce cybersickness. Although Gavgani, Hodgson and Nalivaiko [5] did not examine the Parrot roller-coaster for forward/backward differences, Fig. 9 shows that this is also the case for the Parrot roller-coaster. This provides supporting evidence for [5] where backward motion is proposed to induce less cybersickness than forward motion and supports H2 here.

Fig. 10 shows the cumulative EMV profile for forward and backward motion across focused and peripheral field of views in the Helix roller-coaster. The CEMV metric has identified that both peripheral elements are greater contributors to inducing cybersickness and that the backwards focused FOV is the least likely to induce cybersickness. The backward motion peripheral elements are also better than the forward elements. This result provides evidence that concurs with the research on backward motion [5] and reducing peripheral vision [3], [14] to reducing cybersickness.

Fig. 11 shows the CEMV profile for forward and backward motion across focused and peripheral field of view in the

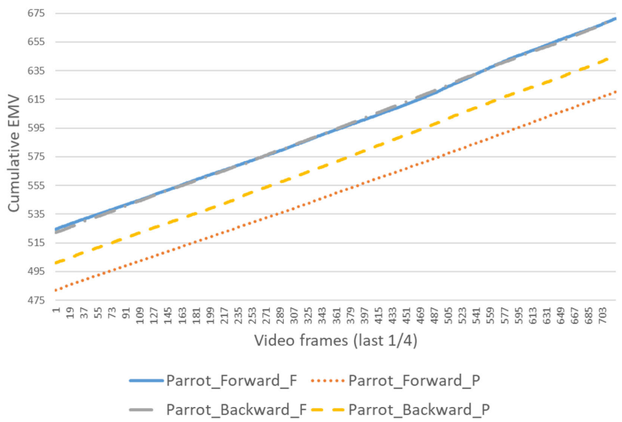

FIGURE 11. Cumulative entropy motion value (CEMV) profile for forward and backward motion across focused (_F) and peripheral (_P) field of views in the Parrot roller-coaster.

Parrot roller-coaster. Again, the CEMV metric has defined a clear separation between focused and peripheral FOV elements that conforms to [3], [14] and also forward versus backward properties [5], at least for peripheral elements. It is interesting to see the similar profile for the focused FOV elements and this may indicate that the Parrot roller-coaster may be, in addition to less cybersickness inducing when compared to the Helix roller-coaster, but also having less variability between forward and backward motion experiences. In summary, the metric has shown that the Parrot has a better CEMV profile which concurs with the user study experiences [6], [7]. Thus providing evidence supporting H3.

V. DISCUSSION

The results have shown that the CEMV metric can differentiate the profiles of virtual environment motion across attributes that are indicative of inducing cybersickness. This is supported by prior research on the two virtual roller-coasters used as the example virtual environments [6], [7], differences in forward and backward motion [5] and the contribution of peripheral visual elements to inducing cybersickness [3], [14]. The work here also builds on the significant volume of research on optical flow for cybersickness research and has produced a hybrid metric with regularity/complexity analysis from entropy metrics and a new cumulative approach to time-series analysis.

Generating such empirical cybersickness profiles, without user studies, could be extremely useful in the iterative development of virtual environments. The CEMV metric would allow different virtual environments, or variations of the same virtual environment, to be compared. This could be used to explore the influence of new features integrated into an environment or provide evidence on the impact of different levels of graphical realism. Fidelity or graphic realism has previously been highlighted as a factor that can increase motion-based sickness [32]. Such an approach would not remove the need for user studies, given that cybersickness is such a subjective phenomenon, but would provide a metric to show improvements in iterative prototypes. This could potentially reduce rework when more robust/completed versions of any virtual environment are required for user studies.

However, the work presented here is not without its limitations. Firstly, the videos captured were from an older Oculus Rift HMD. Motion capture from the older HMD was required in order to provide a fair comparison with the earlier research on virtual roller-coasters [6], [7]. It would be interesting to see whether the output from different HMDs, with different field of view and resolution levels, produced similar CEMV profiles when used in the same virtual environment. This would provide evidence on the impact of display technology on cybersickness inducing motion.

Secondly, the motion data was generated from a stationary view angle. The stationary view angle provides a static view needed to fairly compare the different roller-coaster rides as both environment motion and user-initiated head motion can contribute to cybersickness. In the work here, the focus has been on environmental motion, i.e. the roller-coasters are on rails. Although this is not typical of virtual environment experiences, it does provide a base line for comparing the CEMV profiles between different virtual environments.

Finally, we have only explored cybersickness inducing environments, i.e. virtual roller-coasters. As with the work of [6], [7], the provocative roller-coaster experience aimed to provide conditions that would invoke nausea/cybersickness and provide a strong effect to identify. This effect will likely vary across different types of virtual environments. The extreme form of virtual reality experience reported here is not a typical experience with HMDs. Future work will focus on the use of the CEMV metric in different types of virtual environment and compare the CEMV profiles of virtual environments with limited or no history of cybersickness impact to determine the sensitivity of our approach.

VI. CONCLUSION

This paper outlines an approach to objectively distinguish between self-motion experiences in HMD-based virtual environments without user studies. The aim is to provide design insight from videos of virtual environment motion that can determine cybersickness inducing features as part of an iterative development process. Therefore, initial prototypes of virtual environments, or different versions of the same virtual environment can be compared and improved during development and before moving onto expensive user-based testing. The new approach described here combines optical flow metrics and an entropy complexity measure across focused and peripheral field-of-view components to distinguish between virtual environments. The approach has been demonstrated with two virtual roller-coaster rides that have with known cybersickness impacts. Future work will focus on applying this approach to (i) a wider range of virtual environments and VR HMD technologies and (ii) across environments where data on known cybersickness is available to threshold the accuracy boundaries of the current metric.

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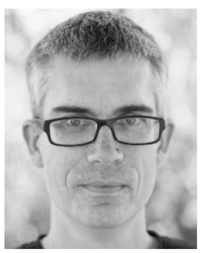

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