An Evaluation of Extrapolation and Filtering Techniques in Head Tracking for Virtual Environments to Reduce Cybersickness

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Abstract. Currently, numerous users who employ HMD devices such as the Oculus Rift develop symptoms similar to motion sickness. Recent literature defines this phenomenon as cybersickness, and one of its main causes as latency. This contribution aims to analyze the accuracy of different extrapolation and filtering techniques to accurately predict head movements, reducing the impact of latency. For this purpose, 10 participants played a VR game that required quick and subsequent head rotations, during which a total of 150.000 head positions were captured in the pitch and yaw rotation axes. These rotational movements were then extrapolated and filtered. Linear extrapolation seems to provide best results, with a prediction error of approximately 0.06 arc degrees. Filtering the extrapolated data further reduces the error to 0.04 arc degrees on average. In conclusion, until future VR systems can significantly reduce latency, extrapolating head movements seems to provide a low-cost solution with an acceptable prediction error, although extrapolating the roll axis movements remains to be challenging.

Keywords: VR · Cybersickness · Extrapolation · Head tracking

1 Introduction

Cybersickness is a term used to refer to the cluster of symptoms that users experience during, or after, Virtual Reality (VR) exposure [1]. It is also known as Virtual Simulator Sickness [2], Visually Induced Motion Sickness [3] and Virtual Reality Induced Symptoms and Effects [4]. Cybersickness is not a disease, but rather the physiological response to an unusual stimulus, similar to motion sickness or seasickness [5]. The reported incidence of cybersickness amongst users of VR is varied, but it is generally accepted that, at least, 60% of participants in a first VR experience will suffer its symptoms to some degree, and although most users adapt to the environment after few immersions, approximately 5% will never do so. The degree of intensity depends on the nature of the VR environment, and previous works have shown it ranges between 60% and 90%, with 5–30% of participants having to discontinue research evaluations due to strong symptoms [6, 7].

The effects of cybersickness can be expected as soon as 5 min once the user starts playing [8–11]. These symptoms disappear once the user stops employing the VR

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googles, but users seem to remain sensitized for hours [9]. Its aetiology is at this point unclear, with three different theories coexisting: That cybersickness is caused by a sensorial discrepancy between the vestibular, visual and proprioceptive systems, that it is the physiological reaction to being incapable of maintaining postural stability, or that it consists on a false interpretation of neurotoxin poisoning [12]. Cybersickness is caused by the perception of self-motion, also known as vection. Head-mounted devices such as the Oculus have already been proven to cause vection and sickness [13], but the way through which vection acts is unknown, and symptoms vary greatly from user to user.

Currently, several factors that have an impact in cybersickness have been identified, and works to analyze the possible causes, as well as to provide design guidelines to minimize cybersickness are under way [14]. For example, personal factors such as habituation [15] or age [16], and task-related factors such as movement speed or controllability [17]. However, it is clear that the most relevant factors are the technical ones, namely the size of the field of view [18] and latency [8]. Research shows that latency values of over 40 ms rapidly cause cybersickness, and higher latencies cause it to appear even faster. Currently, it is generally accepted that latency should be kept at 20 ms or lower, but the reality is that in order to completely cast cybersickness aside, latency should be as close to zero as possible.

Therefore, latency reduction techniques are currently of great interest to reduce cybersickness. Interstingly, in 2013, Prof. Steve LaValle published an article in the Oculus Rift Developer Blog about the possibility of further reducing this latency by extrapolating head position values [19]. However, to the best of our knowledge, such an approach has not been evaluated so far.

The goal of this work is thus to evaluate how accurately is it possible to predict head movements with currently available HMDs, and which is the best method to do so.

This study was performed in the framework of the LOEWE-VR Diagnostics System research project of the TU Darmstadt, in collaboration with the Game Studio DECK 13 Interactive[1] and Software Developer KTX[2]. The aim of this project is to study the possible technical, personal and environmental causes of cybersickness, detect it as it occurs in real time with biosignal analysis and game parameters such as head speed and acceleration, and correlate both biosignals and game variables, with the aim of providing developers with a tool that will help them reduce cybersickness in their released product. Particularly, this study is a first implementation on an array of solutions that may, in the future, reduce the incidence of cybersickness in VR by reducing the disconnection between real and virtual movements.

2 Related Work

The impact of head movements and task-related factors in cybersickness has already been subject of several studies, since it is currently fairly clear that mismatches between real and virtual head movements are a strong cause for cybersickness [20]. For

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[1] Deck13.de.

[2] Ktxsoftware.com.

example, an evaluation with a HMD and two virtual rollercoasters showed that more complex and realistic environments have a greater incidence of cybersickness [21]. Additionally, environments in which locomotion is performed with head movements cause more cybersickness [22]. Research also shows that oscillatory movements cause more cybersickness than linear movements [11], and abrupt turns are believed to increase cybersickness [23], as well as increasing the number of degrees of freedom or providing wider steering maneuverability [23]. Sudden vection also causes cybersickness [24] as does an increase in navigational rotating speed [25]. On the other hand, involuntary movements do not seem to be problematic [26]. Finally, replacing sudden movements with smoother ones, such as stairs for ramps, seems to reduce cybersickness [27], otherwise, compensating head movements is also a possible solution [20]. Head rotations have also been proven to increase nausea [28], and specifically increasing head movements in the vertical direction [29] or looking at one's feet [26].

Evaluations on how rotations in different axes (pitch, yaw and roll) differently affect cybersickness were performed on [11, 28]. Although rotation in all axes increases cybersickness, it seems that rotations in the roll axis are slightly more problematic. Results also show that rotations on two simultaneous axes also increase the risk of cybersickness [30].

By convention, the head rotation vectors are defined as pictured on Fig. 2.

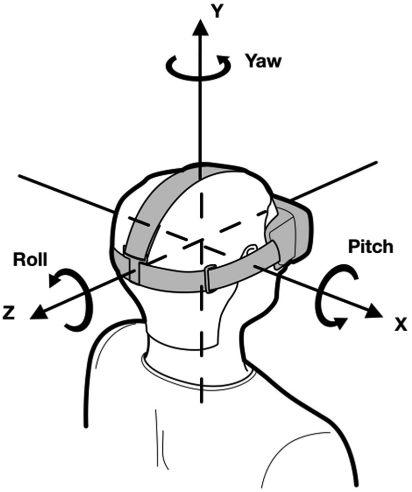

Fig. 1. Head rotation vectors in VR [31].

3 Methods

In order to perform the evaluation, a VR game was developed using the Unreal Engine tool[3] recreating a first person shooter scenario. This scenario was chosen because this genre requires continuous, subsequent rapid head movements in several directions. The

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[3] Unrealengine.com.

game also makes use of the Victory plugin[4] to save the head rotation data. In this game, the player is static, and required to move his head on more than one axis simultaneously in rapid successions to destroy projectiles thrown at him (see Fig. 1). The projectiles are created randomly both in trajectory and number to obtain as varied head movement data as possible. The game was developed for the Oculus Rift Developer Kit 2[5], which has a refresh rate of 75 HZ, that is, 13.33 ms. Therefore different scenarios with increasing refreshing rates (13, 15 and 20 ms) were considered. Since prediction error can be expected to be higher as latency increases, if any of these methods is sufficiently accurate at 13 ms it can be expected to be even more reliable on future devices with even lower latencies.

Fig. 2. Screen capture of the game employed in the evaluation.

By using the mentioned Victory plugin, head tracking data measured by the integrated Oculus Rift head tracking system was saved in a.txt file following a csv structure (Time, Pitch, Yaw, Roll), where values are expressed in milliseconds and arc degrees respectively. These files were then imported into Matlab[6] to perform the extrapolation, filtering and analysis of the results.

A total of n = 10 users participated in the evaluation. Each user played the developed demo for 80 s and three times, pausing for a few minutes between each attempt in order to minimize the effect of cybersickness on the results as much as

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[4] Github.com/EverNewJoy/VictoryPlugin.

[5] Oculus.com/dk2.

[6] Mathworks.com.

possible. This provided us with a total of approximately 150.000 head position vectors, which we then proceeded to import into Matlab.

After importing the data, the pitch, yaw and roll head rotations were extrapolated with three different refresh rates: 13, 15 and 20 ms, attempting to predict the next value, and comparing the extrapolated result with the real value measured by the HMD head tracking device. Additionally, different filters typically applied to smoothen signals (Savitzky-Golay, Moving Average and Local Regression) were implemented and evaluated.

During this work, five different extrapolation methods were considered: Linear, Polynomial (2nd and 3rd degree), Conical, and French curve. However, we quickly noticed only the first two methods provided reasonably accurate extrapolations. We assume the 3rd grade, Conical and French curve methods do not resemble the nature of head movements, since the extrapolation error was of the order of 1000 times higher, and therefore we decided to focus our evaluation to these two first, most accurate methods. We also noticed that extrapolation does not seem to work in the roll axis, at least in the scenario designed in this evaluation, typical of first person shooters, since head movements in the roll axis were infrequent and irregular, and thus could not be extrapolated. We decided to remove roll axis extrapolation from the evaluation as well.

The formulae used for the extrapolation are as follows, with $y(x_k)^*$ being the extrapolated value and $y(x_k)$ the measured value:

Two-point linear extrapolation:

$$y(x_k)^* = y(x_{k-2}) + \frac{x_k - x_{k-1}}{x_{k-1} - x_{k-2}}\left(y(x_{k-2}) - y(x_{k-1})\right)$$

2nd degree Lagrange polynomial extrapolation:

$$y(x_k)^* = \sum\nolimits_{j=0}^{2} y_j \cdot l_j(x_k),\ l_j(x_k) = \prod\nolimits_{0,m \neq j}^{2} \frac{x_k - x_m}{x_j - x_m}$$

Average absolute error:

$$\varepsilon = \frac{\sum_{k=2}^{n} |y(x_k)^* - y(x_k)|}{n}$$

4 Results

Evaluation results are presented in three, subsequent parts. Firstly, we present the accuracy results of linearly extrapolation unfiltered head position data on the pitch and yaw axes with increasing latency values (Fig. 3). Secondly, we present the accuracy of both linear and second degree Lagrange polynomial extrapolation with unfiltered head tracking data with a latency of 13 ms (Fig. 4). Finally, the accuracy of linearly extrapolated data with a latency of 13 ms when using different filtering techniques is presented (Fig. 5). All values are presented in average absolute error in arc degrees, and again summarized in Table 1.

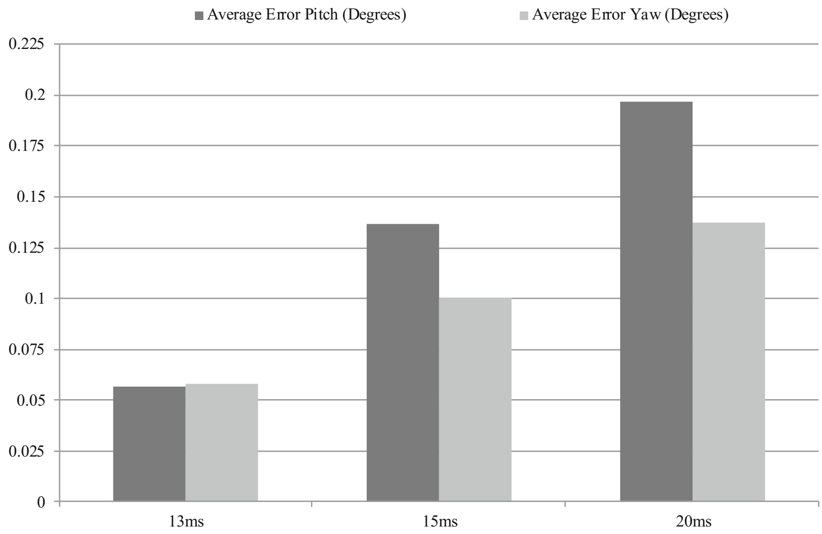

Fig. 3. Evaluation results for increasing timespans of 13, 15 and 20 ms in the pitch and yaw axes. Average absolute error of all values.

According to our results, the best accuracy is obtained when using linear extrapolation and a Savitzky-Golay filter (average absolute error, 0.04 arc degrees), although using other filtering methods (Local regression or moving average) also provides similar results.

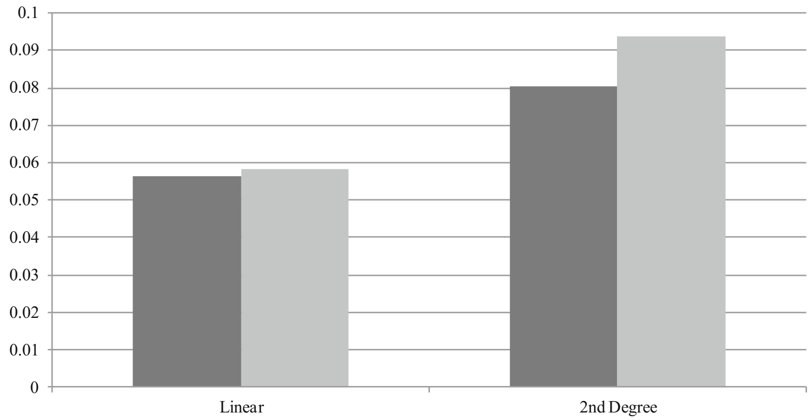

Fig. 4. Evaluation results linear and Lagrange polynomial extrapolation in the pitch and yaw axes with a latency of 13 ms. Average absolute error of all values.

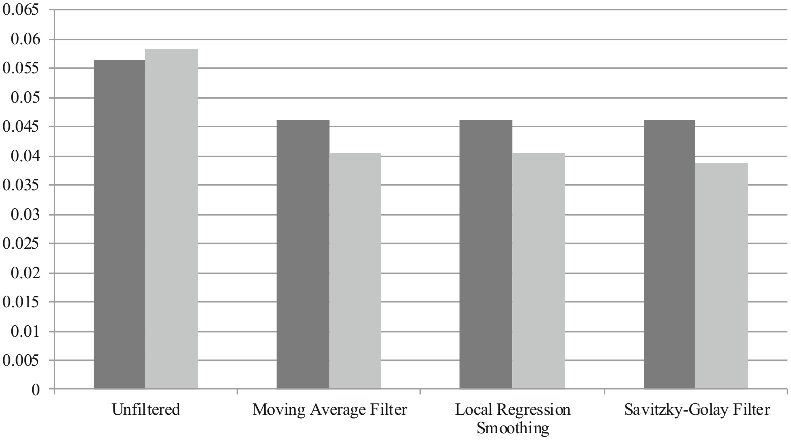

Fig. 5. Evaluation results of filtered head tracking data in the pitch and yaw axes with linear extrapolation and a latency of 13 ms. Average absolute error of all values.

5 Discussion

As it can be expected, prediction error increases with extrapolation time (Fig. 3). We noticed that, in general, the absolute error values are surprisingly low with some approaches, since the first result we obtained by simply using unfiltered linear extrapolation with a 13 ms timeframe was slightly lower than 0.06 arc degrees. This error value indeed increases with time and it does so linearly, although this increase is not equal for the pitch and yaw axes. We noticed that, in our evaluation, the angular acceleration in the pitch axis was normally higher than in the yaw axis, which might explain this difference.

Regarding the extrapolation methods, it would seem that linear extrapolation is more accurate than polynomial extrapolation for both axes, and in turn, both methods are vastly superior to other extrapolation techniques (3rd degree polynomial, French curve and conical). We hypothesize that these extrapolation methods do not resemble the trajectory followed by head movements, explaining this drastic increase in prediction error. Nevertheless, the difference of using either method is reduced compared to the impact of decreasing prediction time.

Results also show that the best method is obtained by combining linear extrapolation with a Savitzky-Golay filter. By using this method, the head position can be extrapolated for 13 ms with an expected average absolute error of 0.04 arc degrees. Again, it is clear that there is an improvement on prediction error by using a filter, but the difference among filters is rather small.

Given the value of this error, and taking into consideration that current technology still cannot provide the processing power required to permit reducing latency to a sufficiently low value where no cybersickness is present, it would seem that extrapolating head movements can provide a reasonably low-cost solution with an acceptable prediction error.

Nevertheless, we are aware of several limitations in this study, which we will aim to improve in our future work. Firstly, due to the nature of first person shooters, our scenario did not require users to perform sufficiently numerous and continuous movements in the roll axis in order to analyze extrapolation accuracy in this direction as well. This could be improved by including a second scenario where roll head rotations may be more frequent, for example a first person perspective flight simulator. Secondly, the number of participants in future studies should be increased in order to determine whether our accuracy results are consistent on a larger user base. Finally, the use of different tracking approaches, for example the IR-based Lighthouse tracking system used in the HTC Vive, should also be taken into consideration.

Therefore, in a future publication, we plan to increase the number users and scenarios and ensure results remain consistent with the ones in this publication, particularly in HMD systems that include bodily movement, such as the HTC Vive, with head movement patterns derived from different typical game environments.

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