Effects of Latency on Aiming Performance for CAVE-like Immersive Virtual Reality Systems and Driving Simulators

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Abstract - *Studies on the influence of latency over performance are mostly made with head mounted displays. The relation between end-to-end latency and performance in virtual and fully immersive environments such as CAVE-like display systems is investigated.*

Keywords: *Virtual Reality, Latency, Performance, CAVE-like Display System*

Introduction

Renault, as others car manufacturers, is relying more and more on Virtual Reality (VR) simulation during the styling and product design of new vehicles. Renault is extending its use of VR to immersive driving simulators and high-definition immersive display systems. Some of the later systems are immersive rooms frequently named CAVE (Cave Automatic Virtual Environment). CAVEs are 3-4m wide cubes with typically up to 4 or 5 faces that are screens. It may include a driver station in the middle for testing in driving situations. These tools are being used for taking critical decisions in multiple engineering fields : design, ergonomics, architecture, perceived quality, ambient lighting, and others. Therefore, these simulators need to reach the maximum perceptual realism possible so that engineers can take their decisions trustfully. CAVE systems are commonly identified as providing scale 1:1 perception of the 3D product, but limitations and questions remain regarding the realism of the perception of the user. Moreover, such systems are basically designed as individual and unique systems, thus providing various levels of performance.

Research Question

There exist several definitions for latency in real time rendering systems [Pap11, Bla15, Wat98]. However, the most common and used definition is the "end-to-end" latency. It can be described as the time elapsed between a movement of the user and its reflection in the virtual environment [Mee03]. It has also been shown that latency has an impact on performance and presence [Man04, Ell99, Mee03, Pap11].

When conducted in immersive environments, these studies were mostly made with head mounted displays. We hence wanted to investigate two questions :

— What is the relation between end-to-end latency and performance in virtual and fully immersive environments such as CAVE-like display systems ?
— What is the influence of latency on presence and cybersickness in such systems ?

If the first question was addressed through perfomance monitoring, the second one was quantified through questionnaires. We focused specificly on the movement of the head and its tracking.

In the latency field, there are different thresholds that can be found in literature : the perception threshold is considered to be around 15-20ms [Ell99, Ade03, Reg99, Man04] while the performance interaction threshold is rather located around 50-100 ms [Jot13, Bro99, Ell99].

Methodology

The subjects were confronted to a life-like situation and asked to perform a typical daily task such as looking at precise locations in a vehicle, during short amounts of time. The immersion was done through the mean of a 4 faces CAVE-like display system, with the subject seated at $1\ m$ far from the main screen. The subjects were to perform an identical routine at different levels of latency. The simulation ran at a smooth 60 frames per second. Performance indicators established beforehand were transparently recorded during the routines. In addition, multiple questionnaires were filled throughout the entire experiment : immersion tendency [Wit98], presence [Wit98] and simulator sickness questionnaires (Kennedy's SSQ). The scientifically verified french translation of the questionnaires were used [Bou07, Bou09, Bou11].

Precisely, the subjects are immersed in a realistic-looking car and its environment. They were asked to

Figure 1: View of the life-like setup. The current indication is "left target" while the red reticle is on the top of the central display.

visually aim at given points in the car, in a random order. The aiming was helped with a game-like virtual reticle follwing the movements of the head. The target to aim at were indicated by means of a white arrow pointing one out of four possible directions (left, up, right and down). Whenever the subjects assumed to be at the center of the designated target, they would hit a button on a joystick they held in their hands. There were four different possible targets, bounded to the direction of the arrow : the left and right mirrors, the rear view mirror and the central display. The routine was made of 24 targets to hit (6 times each of the 4 targets) presented in a random order. The subjects were asked to replace their gaze at the arrow location after every aiming routine. The software automatically and covertly recorded the hit position on the target (x-axis and y-axis coordinates) and the hit time. The hit position was then used to compute how far from the center of the target the subject shot. The output is relative to the size of the target and thus given between 0 and 1 on both axes.

The same 24 targets aiming routine was performed twice : once at the standard running capability of the immersive system (reference setup) and once in a degraded state of the system, latency-wise. The order was alternated between subjects in order to limit any bias. Latency was added on the tracking of the head. Technically, the tracking is correctly performed but delayed in time. We did not degrade the frame rate to be able to keep a high frame rate and thus a smooth (but late) simulation.

The latency offset we added in our experiment is based on the different values that were presented previously in the Research Question section. In order to stay within the range of the performance interaction threshold, we chose to add an amount of $60\ ms$ within the tracking loop of the head (Fig. 2). The addition of latency was made by applying a filter in the tracking software. The filter was set with a negative amount of anticipation time.

In order to properly conduct our experiment, some values needed to be verified upstream. We had to measure the total amount of latency, with and without added latency (and hence verify that the filter is well applied). There exist a lot of different techniques to measure end-to-end latency [Pap11]. Since our system tracks the VR glasses, we chose to apply a color tint to the 3D environment, based on the height difference of the tracked device (compared to the height at the previous frame). For a positive difference (actual height greater than previous-frame height) the world was tinted green while for a negative diffrence

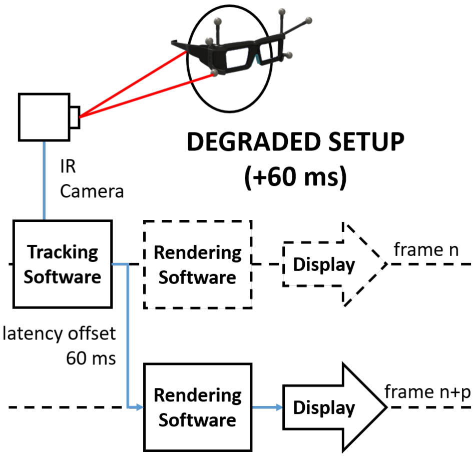

Figure 2: Technique for delaying the tracking information.

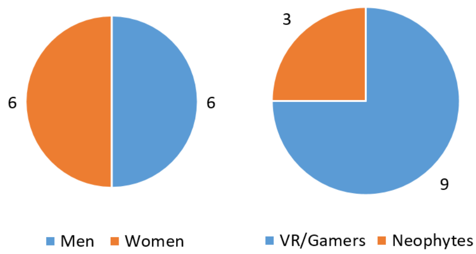

Figure 3: Distribution of the population of subjects for the experiment.

(actual height smaller than previous-frame height) the world was tinted red. We then applied a sinusoidal vertical movement to the glasses and filmed the output (glasses + screens) at 120 Hz. By running frame by frame the thus obtained video, we could count the number of frames between a real change of direction of the glasses' movement (ascendent or descendent) and its display (which was characterized by a tint change of the 3D environment). The precision is hence half a frame, which means $4\ ms$. Our measurements report a total amount of latency of $160\ ms$ for the reference system, and a correct addition of $60\ ms$ in the tracking loop, which leads to a total amount of latency of $220\ ms$ for the degraded setup.

In our experiment, there were 12 subjects, 6 men and 6 women, aging from 23 to 54 years-old, with a mean value of 31 y.o. and a standard deviation pf $\sigma = 11$ y.o.. 9 of them declared being familiar to Virtual Reality or playing video games (Fig. 3).

This study is carried out as a preliminary one and therefore presents only a small panel of subjects with a low performance (high latency) CAVE. It opens the path to a future larger-scale study, especially with low-latency systems such as HMDs.

Results

The immersion tendency questionnaire (Fig. 4) gave back an average value of 44.58 out of 70 (standard-deviation : $\sigma = 8.81$) while the presence questionnaire had an average response value of 68.92 out of

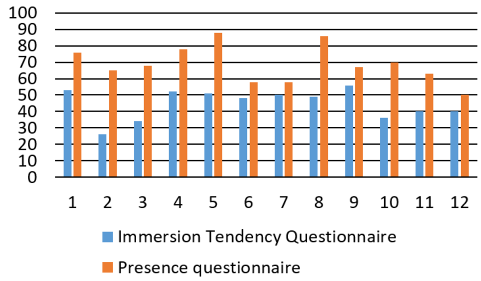

Figure 4: Comparison of the Immersive Tendency Questionnaire and the Presence Questionnaire for all 12 subjects.

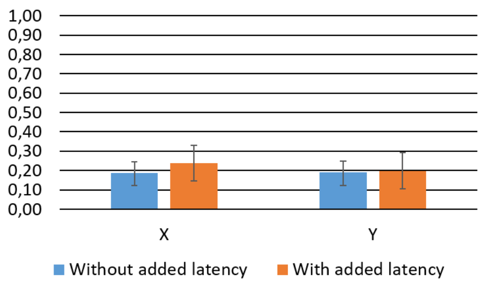

Figure 5: Mean values and standard deviations for the aiming accuracy on both axes and setups.

91 (sd : $\sigma = 10.96$). The initial simulator sickness questionnaire (SSQ) returned an average value of 3.58 out of 48 (sd : $\sigma = 3.01$) while the non-latency-degraded setup returned an average of 2.75 (sd : $\sigma = 2.01$) and the latency-degraded-setup returned 6.08 (sd : $\sigma = 6.42$).

The aiming precision is calculated as the average precision on an axis for all targets (i.e. all 24 trials). For the non-latency-degraded setup (Fig. 5), the x-axis relative precision of the subjects shooting on targets was 0.19 (sd : $\sigma = 0.06$) and, equally, 0.19 for the y-axis relative precision (sd : $\sigma = 0.09$). The average completion time was 96.79 seconds (sd : $\sigma = 12.46$). The time per target was evaluated at a mean of 4.03 seconds (sd : $\sigma = 0.52$).

On the second setup, latency-degraded (Fig. 5), the x-axis relative precision of the subjects shooting on targets was 0.24 (sd : $\sigma = 0.06$) and 0.20 for the y-axis relative precision (sd : $\sigma = 0.09$). The average completion time (Fig. 6) was 121.78 seconds (sd : $\sigma = 17.07$). The time per target was evaluated at a mean of 5.07 seconds (sd : $\sigma = 0.71$).

Most of the statistical tests were done using the Welch two sample t-test. The alternative hypothesis was "less". The significance threshold was set at $\alpha = 0.05$. The Welch test was used to determine whether the latency conditions had influence on the precision of the subjects on the x-axis, the y-axis, on the total completion time, the time per target and the variation of the simulator sickness questionnaire results (Tab. 1). In addition, a Pearson correlation test was used to explore the relationship between the immersion tendency questionnaire results and the presence questionnaire results.

The immersion tendency versus presence test has a p-value of $p = 0.280$ and a correlation factor of

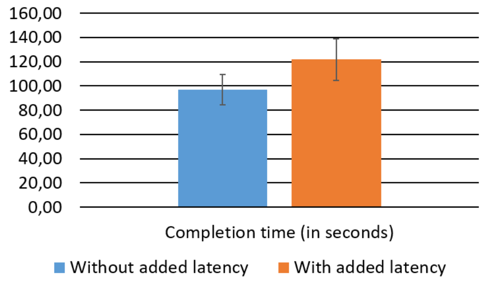

Figure 6: Mean values and standard deviations of the completion times for both setups.

$\rho = 0.340$. The statistical test between the two simulator sickness questionnaires returns a p-value of $p = 0.0620$.

The Welch tests on the influence of comparison between the x-axis precision at lower latency setup and higher latency setup returns a p-value of $p < 0.05$ while the one on the y-axis aiming precision returns a p-value of $p = 0.395$, the one on the completion time returns a p-value of $p < 0.001$ and the last one, on time per target, returns a p-value of $p < 0.001$.

Table 1: p-values of the Welch two sample t-tests (alternative "less").

Response variable	Degrees of freedom	p-value
x-axis precision	22	0.0378
y-axis precision	22	0.395
completion time	20	0.0004
time per target	20	0.0004
SSQ value	13	0.0620

Discussion

Our results show a statistical influence of the latency on the accuracy. When the increase of latency happend, the subjects were 26% more inaccurate on the lateral movements and 5% less accurate on the vertical movements. The inequality between the two axes could be explained by the greater movement amplitude needed to reach the left and right targets (left and right mirrors, between 40 et 60 degrees) compared to the amplitude needed to reach the top and bottom targets (central mirror and central display, 15 degrees). A larger movement means a longer interaction time with the latency and hence a higher imprecision.

Another great parameter that must be taken into account is the fast completion of the 24-targets routine that was asked. Keeping a high pace during the experiment implies less care given to to accuracy of the aiming. Hence, our results show a poorer accuracy compared to what could have been reached whether the order would have been to simply aim at the center of the targets. The average accuracy of the subjects above the median of completion time (in the higher latency setup) is greater than the average accuracy of the subjects below the completion time median : 0.26 against 0.21 on the horizontal axis and 0.23 against 0.16 on the vertical axis. Hence, as well as the interaction time, a higher pace under higher latency condition leads to a higher imprecision.

Our results also show a statistical influence of latency on the global completion time (with an increase of 26% over the degraded setup) and the time per target, which is directly linked. Finally, we can observe a large increase of the SSQ values between the two setups (+121%). However, the statistical significance is just above the threshold showing a weak correlation. This can be explained by the average SSQ degraded setup value being bumped by very high sickness values from a few subjects. On top of the classic vergence-accommodation conflict that causes sickening, there is an other conflict that contributes here to the increase of simulator sickness : the visio-vestibular conflict. The more latency, the more disparity between vision and consciousness of the movement by the vestibular system and hence sickness.

Unfortunatly, we were not able to predict the presence feeling based on the immersive tendency questionnaire answers. The statistical correlation between the two could not be demonstrated. However, this may be heavily resting on the system's specifications.

The more speed in the head movements, the more latency influences user experience ; both in accuracy degradation and in simulator sickness increase. The subjects were facing a choice : either they would slown down their movements to achieve better first intention target aiming or they would keep a good pace to the detriment of accuracy and sickness. The subjects seem to develop their own strategy to counter the offset of latency, based on how heavily they were burdened by latency. As a result, to ensure the best user experience and the minimize the effect of sickening, it might be advised to suggest slow and small movements to the daily users of the immersives techniques.

Conclusion and Future Works

An experimentation was performed to observe the influence of "end-to-end" latency on an seemingly daily task. Objective measurements were carried during the experiment. The subjects also had to fill several questionnaires such as immersion tendency questionnaire, presence questionnaire and simulator sickness questionnaire.

Our results statistically show a degradation of the accuracy, for the lateral movements, on the targets to aim and an increase in the time required to perform the full 24 targets routine. In addition, there seems to exist a weak presomption of influence on the evolution of simulator sickness with latency. However, we were neither able to significantly show an influence of latency on the vertical movements accuracy nor to prove the existence of a correlation between the immersive tendency questionnaire and the presence questionnaire. These results allow a better understanding of the effects of latency on performance in CAVE-like immersive display and on the strategies subjets may be brought to deploy to maximize their experience.

Still, there are improvements that can be done to the current experimental setup. The aiming reticle is only attached to the movement of the head and could be driven directly by the movement of the eye. However, this technology takes a heavy toll as it typically adds around $100\ ms$ to the global latency. In addition, our current "end-to-end" latency could be drastically reduced by upgrading our projectors.

All in all, this opens the path to a new set of measurements and a comparison between our CAVE-like display system and a Head-Mounted Display (HMD). The new experiment would take place in the same 3D environment and on the same routine basis. This would allow to reach lower latency setups and to investigate whether the subjetcs deploy the same strategies within an other immersive display.

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