Heading Towards Eye Limiting Resolution – Display Systems in Driving Simulation

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Abstract *– In driving simulation the driver looks through the windscreen into the virtual world. Besides of the content that is displayed the quality of the display system, i.e. the projector used, plays an important role. It influences the perception of the driver and thereby his behaviour. At BMW Group Research and Technology most recently three new display systems with a wide field of view were installed. Once the requirements were defined detailed tests with various projector types were done. This paper is a summary report of the work done and experience gained over the last years. This summary is independent of specific suppliers and focuses on principle characteristics. Different technologies of projectors as they are relevant for the use in driving simulation are mentioned including their basic properties. Human visual perception and spatial as well as temporal resolution is introduced. The various tests that were done with the projectors and their relevance to the use of driving simulation are addressed as well as experiences and aspects that have to be taken care of are mentioned. Finally the three new display systems for the dynamic driving simulator and the fixed base driving simulators in the Centre of Driving Simulation and Usability at BMW Group Research and Technology are outlined.*

Introduction

In every driving simulator some kind of display system is used to present the image of the environment to the driver, i.e. the view into the virtual world. The type and quality of the display can vary significantly. It is well known that poor display quality can severely increase the nausea feeling of the driver. As well the appropriate judgement of the driver on whether a traffic situation is critical or not depends on the correct visual perception. The judgment e.g. on an oncoming truck which the driver can see when starting the manoeuvre of over taking a slower car depends on whether the driver can identify that there is an object approaching and he can recognise the type of the object. As well the estimation of distance and speed which is linked to the identification of the object itself is influenced by display quality.

In the Centre of Driving Simulation and Usability various kinds of driving simulators are installed fulfilling the demands of different kinds of examinations. In the build-up and renewal of these simulators much care is taken of the quality of the display systems. In order to gain appropriate perception with respect to the requirements of a specific driving simulator BMW Group Research and Technology spends much effort in the testing and selection of display systems.

Today's Projector Technologies for Simulation Application

There are various projectors out there on the market and one can spend from one hundred up to approximately one million Euros. There are various customers asking more and more for high quality projectors. The home cinema is one of these areas leading to high quality products at a comparable low price.

Nevertheless the needs of simulation business are very specific. A high resolution, i.e. lots of pixels, is a clear requirement. This resolution is called spatial resolution. The high resolution image shall be perceived as such even in a dynamic environment. This is referred to as temporal resolution defining the perception of an object or scenery as it changes in time. Only in case of negligible blurring artefacts the visual conditions for static and dynamic sceneries are equivalent and so the temporal resolution is of high quality.

In the following the common technologies of projectors used in a driving simulation environment are listed. These are basic information necessary for the discussion afterwards. Detailed information can be found in internet, e.g. [2] or at the sites of various projector suppliers.

CRT (Cathode Ray Tube)

The CRT projector is a reference since the beginning of driving simulation. The image is composed of a sequence of displayed image points created by a single ray. Every pixel is highlighted only a fraction of the time available for every frame. The overall brightness of the image is very limited. The colour is composed by the three basic components red/green/blue whereas the convergence is done at the surface of the screen and not within the projector. This requires a huge amount of calibration effort which has to be done continuously. An advantage of that technology is that practically there is no delay in displaying the image once the signal is at the projector. Due to the fact that every pixel is highlighted only a very short time there is no visual artefact of blurring, caused neither by the projector technology nor by human perception. This projector type is the standard for issues of temporal resolution.

LCOS (Liquid Crystal on Silicon)

The LCOS technology is a digital full image one, i.e. for every pixel of the image there is a corresponding entity on the chip. LCOS technology is similar to

LCD technology but in contrast to sending light rays through the chip a polarised ray is reflected. The switching of the state of a pixel needs some time and therefore there are transition states between the frames which can be observed as blurring in moving scenery.

Every pixel is highlighted all the time of a frame, i.e. 16.6ms in case of 60 Hz. The brightness is much higher compared to CRT but part of the brightness of the projector lamp is lost due to the fact that polarised light is used in combination with the LCOS chip. Colour convergence is done within the projector. For each of the three basic colours a separate chip is used. Maintenance of the projector is reduced to changing lamps and filters. The LCOS technology has the advantage of extremely low delay which is almost comparable to CRT in case of undistorted images. Once using any warping functionality an additional delay has to be taken into account. This is due to the fact that there is no pixel by pixel relation between the rendering output of the graphics card and the display chip of the projector anymore. Typically it needs information of pixels of several lines of the rendered image to compile a single line of the projector. This algorithm leads in total to a delay according to the number of lines necessary to compile one line of pixels for the projector.

DMD (Digital Micro Mirror Device)

The DMD technology is the basis used in a kind of projectors better known as DLP projectors (Digital Light Processing, trademark owned by Texas Instruments). Similar to LCOS technology there is a chip with reflecting parts for each pixel. In this case there are micro mirrors that are modulated such, that within the period of an image frame the light is partially transmitted through the optics and partially at a light absorber. By this, different light intensities can be created. The switching time of the mirrors is very fast. The modulation frequency is up to 5000Hz. There is a delay of one frame between the time the data arrive at the projector and the image is displayed, i.e. before displaying an image the complete information of the frame has to arrive at the projector.

Colour convergence is done in two different ways. In case of a single chip projector the colour is sequentially combined, i.e. within a frame of display time using a colour wheel or comparable technology (e.g. coloured LEDs) the three basic colours are displayed at the screen, one after the other. In case of a three chip projector the colours are presented at the same time and colour convergence is done inside the projector. Caused by the mirror technology there is more brightness of these projectors compared to LCOS and the maintenance is very similar.

GLV (Grating Light Valve)

The GLV is a micro electro-mechanical system used to reflect light. It is similar to DMD technology. A major difference is that the device covers one column of pixels of an image at once and the image is composed sequentially by the human eye and brain. Creating the sequence of columns at the screen mechanical mirroring devices are typically used. Furthermore laser light sources are used.

Therefore this technology has comparable advantages as single ray laser projectors.

Single Ray Laser Projector

In case of a single ray laser each single pixel is created by the laser source and, using mirroring devices, sequentially the whole image is projected to the screen. This is very similar to CRT whereas in case of CRT the convergence of colour at the screen requires a high accuracy of adjustment. In case of the laser the colour is created inside the projector and for the single rays no focus is necessary. Laser light provides an extended colour space compared to other light sources.

Human perception and temporal resolution

Judging the above mentioned characteristics of projector types it is necessary to know some basics about human visual perception of moving objects. The main topic here is whether an image is perceived as having blurring artefacts or not. There are mainly two reasons for blurring due to digital projection.

The first is linked to the ability of a projector to quickly switch between images. Assuming (as an extreme case for better understanding) a video showing a slow moving object (black box on white background) and a display that needs more than one frame switching between black and white (and vice versa) one can easily imagine, that the black box would have a grey and blurred contour at the front with respect to the moving direction and a grey tail at the rear. This perception is only due to the assumed technical capability of the display.

The second reason for perceiving an image as blurred is that human has a high performance sensor, processor and controller for vision. While looking at a moving object in reality it is possible to continuously focus on that object. This is possible because there is a continuous adjustment of the viewing position. The evolution of human being is not tuned to having something digital as 60Hz frame rate.

In case of having a perfect sequence of images at e.g. 60Hz, the result is a jumping image every 16.6ms. Looking at a video there still is a continuous moving of the eye but a discrete jumping of the displayed images. Therefore a moving spot in the video is moving back and forth on few receptors on the retina and not staying on a single position. This is perceived as blurring. This artefact occurs once the image is displayed more or less over the whole time of a frame. In case that the image consists of single light spots, which are displayed in a sequence, the light is seen only a fraction of the frame time and thus no blurring can be seen. This is the case when someone is looking at a CRT projection.

The way to reduce such perceived blurring is to reduce the time of exposure, i.e. to show the image only part of the time of a frame and the remaining time the display is black. In this manner switching times necessary to change a pixel can be hidden as well.

Such options are offered by some companies specialised on simulation projectors based on LCOS and three chip DMD devices. The compromise of this procedure is that the light output of the projector is reduced accordingly.

The Test procedures

At BMW Group Research and Technology various projector technologies were tested and compared. This was done in order to decide on the appropriate projectors for the new display system for the dynamic driving simulator as well as for two systems in fixed base simulators. The procedure that was used to test projectors was developed in a pragmatic way step by step according to the increasing experience. The aim was to judge on projectors using driving simulation situations and scenarios as these give the correct and detailed information with respect to the environment in which the projectors would be used. As part of these tests were done at the facilities of the suppliers a transportable computer configuration was used including SPIDER [3], the driving simulation software of BMW Group Research and Technology.

In the area of flight simulation almost at the same time tests were done with various display technologies focusing on the perception of moving objects. Meanwhile the results are published [4, 5, 6]. Although using different image content and methods the results are quite similar to those gained by the authors.

Spatial Resolution

When replacing projectors the aim always is to increase visibility conditions. In a common sense this is linked to the spatial resolution of a projection system. Taking human perception into account it is clear that spatial resolution is only one criterion amongst others. But definitely the spatial resolution is the basis. As the visibility conditions for moving objects can never be better than for a static image the first step of testing is to look at spatial resolution only.

In order to test other projector technologies and the advantage of increasing the resolution, side by side tests were done. For the first system to be selected which was the projection system of the dynamic simulator, the existing CRT projectors were the reference with a resolution of six arc minutes per optical line pair (6'/OLP). The tests were done with LCOS and DMD projectors of various kinds. The GLV and single ray laser projectors were not tested because on the one side the price for such systems was not within the available budget and on the other hand projectors as they are on the market today were not yet available.

The projectors to be tested were installed with a resolution of 3.5'/OLP to 4'/OLP. Although the final configuration would have a curved screen, the tests were done on a planar screen. In this configuration a dot by dot mapping of the generated image to the projector pixels is done and thus artefacts due to a warping unit are avoided

There are different situations in driving simulation that can be used to judge visibility with respect to resolution. One is to compare the maximum distance between a road sign and an observer so that reading the sign still is possible.

This test was done using an exit sign on the motorway. These kinds of signs can typically be read in a distance of round about 250 m-300 m. In the tests done the sign could be read in a distance of 50 m-80 m using a low resolution CRT and in a distance of 150 m-180 m using a higher resolution projector, no matter of what type.

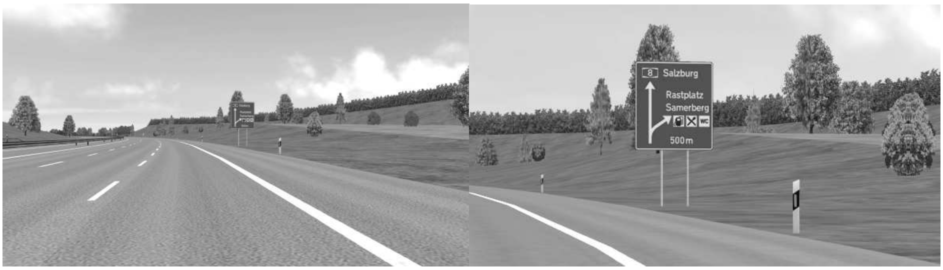

Figure 1. Judging visibility condition by reading a road sign

Another important question is whether an observer is able to identify objects in a far distance. Looking along a road in the city was chosen as a representative situation. The road and the objects along the road such as pedestrians, parking cars and others were compared. A further question was whether it is possible to recognise that there is a T-crossing at the far end. There are several criteria for this assessment. One is to recognise that there is a building at the end of the road. Another is to identify cars (i.e. moving objects) driving in cross direction.

Figure 2. Judging visibility condition by looking along a road and identifying objects

The results of these tests showed that increasing the spatial resolution led to a significant increase in visibility. The image was perceived to be clear and sharp with the increased resolution. This result was quite independent of the technology of the projector.

Temporal Resolution

After conclusion of the tests for spatial resolution it is important to know whether the visual quality is still available if the objects move. In a driving situation moving objects appear once the subject starts driving. In case of longitudinal speed (e.g. driving along a motorway) there occurs different moving of objects on the screen. Objects at the far front move slowly on the screen whereas objects in the vicinity of the driver move quickly and change their size at the same time. This situation is difficult for judging blurring effects. A better situation is the rotational speed of objects that occurs when turning at a crossing. In this case all objects have the same speed on the screen and the size almost does not change. This is definitively easier to use for judging on temporal resolution.

The set-up used for investigation was a T-crossing of roads. The virtual camera was set in the centre of this junction and a rotation around the vertical axis through the camera was applied. Off course, this scenery is not easy to watch for everyone especially as rotational velocity increases. The tests were done always starting at low speeds. The maximum speed at which it was possible to judge on visual perception and thus on temporal resolution was 25°/s. This is comparable to a manoeuvre of quickly turning at a crossing.

Figure 3. Representation of the crossing used to judge on spatial resolution. The upper image is composed of four images in the direction of 0°/90°/180°/270°. The lower part shows details t hat were used to decide on readability

The readability of road and traffic signs was one of the criteria to be evaluated. These signs were, as a reference, easy to read as long as the virtual camera was not in motion. The faster the rotation got the more difficult it was to read the text. Besides of the readability other characteristics were monitored, e.g. how vertical edges of houses or the structure of fences appear.

This rotational scenery was used as well to judge on the type of artefacts that a specific display technology would bring up. This was blurring, colour break up or kind of shadows depending on the projector technology. In this case only projectors that reduce the time the image is displayed (as described before) lead to really good results, i.e. the moving scenery was perceived as good as the non moving scene with respect to the criteria mentioned.

Experience

Besides of the results already mentioned further experiences were made which are important for projector tests and decisions on projection systems.

First of all it is very important to know about the settings of a projector once doing a comparison. As high performance projectors are designed to support various use cases a lot of features modifying the video signal exist. As in case of moving images blurring is something to avoid features that are built in the projector to increase sharpness or contrast have to be switched off as they lead to wrong results.

For the well being of a subject in a driving simulator the level of spatial and temporal resolution has to be almost equivalent. This was the result of a test that was done with a small number of subjects. Each subject had to sit on a chair in front of a screen and watch a driving scenario as if he was in the driver's seat. The subject had to judge on two different visual configurations. One with a resolution of 6'/OLP and the other with 4'/OLP. Both setups were displayed using a single chip DMD projector with colour wheel.

No matter whom we asked, once entering the test site with an image not in motion the higher resolution image was the really impressive one. But, as soon as motion of the image started there was a significant drop of perceived resolution. Subjects mentioned that everything is getting blurred. This effect was even more dramatic once driving with slightly deviations from the straight line. The blurring resulted from the yaw component of motion. In case of the 6'/OLP configuration the difference in perceived spatial and temporal resolution was less and therefore the overall quality (I'm feeling well) was judged better.

With increasing resolution more and more projectors are necessary to maintain a wide field of view (FoV). The more blending zones there are, the more possibilities exist where mismatches can occur. In order to gain a perfect and continuous image an extremely good edge blending is necessary. The adjustments necessary are of the dimension of a single pixel. In order to reduce the continuous effort necessary to maintain the high accuracy in the blending area an auto-calibration system is helpful.

Software blending, i.e. using continuous grey levels at the blending boundaries is easier to realise than hardware blending and at least for day time driving sceneries a good solution. But care has to be taken in case of DMD technologies as the grey level is a result of different modulation of the micro mirrors. Some chips use synchronised modulation for all equivalent grey levels. This leads to the artefact of flickering bands that human eye can perceive in the blending zone especially in case of saccadic eye movements.

A further issue that comes up with high resolution displays is that synchronisation gets more and more important as minor differences along the blending edges can be perceived. In order to run high resolution perfectly we introduced software synchronisation of the image generators into the driving simulation software SPIDER. Furthermore a hardware synchronisation between the graphic cards was installed.

Looking at the layout of a high resolution display the characteristics of human eye should be taken into account. The eye limiting resolution of approximately 2'/OLP is only available in the fovea of the eye. This is a very limited area of at the maximum a few degrees of angle. In this central area the subject is able to focus and have sharp vision. Thus the high resolution of a display system has to be installed only in the area where the subject is focusing at. In case of driving simulation tasks this is the road and the vicinity around as the driver continuously is scanning this area. Typically this is the area directly in front of the car. One can enhance this area as to be the area that can be seen through the windscreen at the front which is roughly 30° to left and 50° to t he right in case of a left-hand drive. For the peripheral area less resolution is sufficient. As there is a significant increase in perceived resolution once changing from 6'/OLP to 4'/OLP one would expect that the change in resolution can be clearly seen in a projector setup with varying resolution. Our experience is, that once the display is really continuous with respect to geometry, colour and brightness the change in resolution is something that subjects will not be aware of.

Changing from CRT to any digital projector there is a lot of light available. Although the contrast value given for a single projector is in the range of several hundreds to thousands the overall contrast of a wide field of view projection system is in the order of ten. The reason for this is that there is a lot of scattered light which changes the black level to a kind of grey level and thus reduces the available contrast. An approach to increase contrast of a unity gain screen is to reduce the gain, i.e. to change from a white to a grey screen. The effect of increasing the contrast is based on the fact that the scattered light is reduced and although the overall brightness decreases the contrast achieved increases.

This was an issue as well once fine tuning the new display systems at BMW Group Research and Technology. Doing tests with several tiles having different levels of grey the common opinion was that having a brighter image is preferable compared to an image on a grey screen that would have a higher contrast.

New Projection Systems in the Centre of Driving Simulation and Usability at BMW Group

The different kinds of simulators in the Centre of Driving Simulation and Usability as well as the scope of examinations were presented earlier [1]. The projection systems mentioned here are those of the dynamic driving simulator and of two fixed base simulators with a wide FoV.

These projection systems have some of the requirements in common. The horizontal FoV should at least be 220° and the vert ical FoV should be 24° to the top and 20° to the bottom based on a height of the driver's eye point of 1.15 m. The eye point distance should be greater than 3 m and the spatial resolution should at least be 6'/OLP and significantly smaller in case of the high resolution systems whereas reasonable placements and amount of blending areas had to be achieved.

The Dynamic Driving Simulator

The dynamic driving simulator was equipped at the start with three CRT projectors presenting a 180° horizontal FoV image t o the front at a spatial resolution of 6'/OLP to 7'/OLP. The decision on this projection system was taken once with respect to the excellent temporal resolution of CRT.

The upgrade of this projection system was the first project to start with. The requirements were to increase horizontal FoV to at least 220°, to increase brightness, to increase spatial resolution aiming for 3'/OLP and to get a system with significantly less demand for maintenance. As the blurring artefacts of moving images displayed by CRT projectors are not recognisable the reference quality was at a very high level. The system to be selected should be on the same level.

The various projector tests showed that the high resolution requirements asked for a projector that would have minimal blurring artefacts in order to guarantee that the high spatial resolution would still be perceived once the objects move and thus fulfil the requirements of temporal resolution as well. Therefore only those projectors came into consideration which are equipped with a kind of a shutter functionality (no matter whether mechanically or electronically) in order to reduce the exposure time of every image of a frame. Best results were gained with a 50% blanking period.

The weight of the projection system was a critical issue as well. As the projectors are mounted on the ceiling of the dome they are critical with respect to the Eigenfrequency of the overall system. The compromise was to select a seven projector configuration (DMD) with a high resolution of 4'/OLP in the front (120° symmetric distributed to the right and left using five projectors in portrait format) and 6'/OLP at the side building in total a horizontal FoV of 240°.

A New Fixed Base Simulator

After exchanging the projectors in the dynamic driving simulator the next task was to set up a new fixed base driving simulator that should be comparable to the dynamic driving simulator with respect to resolution and FoV.

For this purpose several projectors were tested. The reference was now the high quality projector (DMD technology) used in the dynamic driving simulator. The common requirement was to achieve a resolution of approximately 4'/OLP in the front of the driver and to be able to project on a cylindrical screen. As the budget available was less than for the previous system the question was which compromise had to be made. The tests done showed that if the high resolution to the front is a fixed requirement the projectors to be considered were the same that came into consideration for the dynamic driving simulator. Thus the trade-off was to reduce the high resolution area at the front, slightly reduce resolution and reduce the total horizontal FoV to 220°. The configuration selected consists of three projectors in portrait format to the front and two projectors at the side in landscape format. Once again there is a decrease in resolution from the centre to the side projection.

The Upgrade of the existing Fixed Base Simulator

The existing fixed base driving simulator is in operation since many years. It had a five channel display system with 225° horizontal FoV using LCOS technology. During the projector tests comparisons were made to these older projectors as well. It could be seen clearly that even without changing the resolution an improvement of visual perception could be gained by exchanging the projection system.

For this projection system the requirements on resolution were less than for the previously mentioned fixed base simulator. The concept of the different driving simulators in the Centre of Driving Simulation and Usability provides differently equipped driving simulators such that the decision which simulator to use is based on the requirement of the specific examination. This made it possible to exchange the existing projection system although the available budget was significantly less than for the new fixed base simulator mentioned before.

The projection system selected is based on three single chip DMD projectors covering almost 220° horizontal FoV on a cylindrical screen. The spatial resolution is approximately 6'/OLP. A significant higher resolution was not acceptable as the projectors do not have any feature of reducing the exposure time of every image of a frame and thus reduce the perceived blurring of digital projectors. The wide FoV for every projector requires a very flexible warping unit in order to set up the geometry correction. Another issue is that the performance of the image generator i.e. the graphics computer is even more critical than for the other projection systems mentioned as the content to be rendered is larger than for the other systems.

Conclusion and Acknowledgment

With this paper the authors want to share their experience with others involved in similar tests and decisions. All in all this is the summary of the tests done over several years, starting with the first projector test up to the time all the three simulators were equipped with a new projection system.

It is neither the aim to give an advice on which projector to use nor which supplier to choose as technology and products on the market change continuously. Requirements vary for different simulators and not at last the available budget influences the possibilities. Therefore for any selection individual tests are necessary for which the given information is helpful.

The intensive testing of various projectors would not have been possible without the support of projector suppliers. The authors want to thank those involved in the testing for their intensive support and fruitful discussions.

Keywords: Driving Simulation, Projector Technology, Display System, Visual Perception

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