NADS IMAGING SYSTEM UPGRADE

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ABSTRACT

After many years of service, the National Advanced Driving Simulator needed a new imaging system. The existing projectors and image generator [IG] had become outdated and worn out. The old projector system was replaced with a new design using LED projectors. The old image generator was replaced with a cluster of PCs using NVIDIA GPUs. The new systems were designed and integrated in-house. Software was developed for the image generator and for projector control and tuning.

Topics discussed regarding the projector system include: Projector system design strategy; projector selection process; mounting system; video and control signal distribution; projector control software; and projector alignment and tuning software.

Topics discussed regarding the new IG system include: IG system design strategy; cluster control and synchronization; communication protocols; rendering software; and image warping and blending software.

INTRODUCTION

The visual system (including both projectors and image generator) at the National Advanced Driving Simulator (NADS) was old, unreliable and obsolete. Within funding constraints, a new system was designed and assembled from commercially available components to fit the existing dome structure. Existing rendering software developed by NADS was extended to allow its use in a multiple computer rendering system.

BACKGROUND

After many years, the National Advanced Driving Simulator needed to upgrade its visual system, including both image generator and projectors in the NADS-1 driving simulator. The existing system had become obsolete, unreliable, and its performance had degraded since its initial delivery. The NADS-1 driving simulator has a 13 degree-of-freedom motion base, and a 360 degree field of view. NADS-1 is primarily used for human factors research of driving in both day and night time studies.

The upgrade involved selecting new projectors, and designing hardware mounts, video distribution, and a new IG.

Since the spherical dome of NADS-1 provides a 360 degree view, the visual system must provide both warping and blending functions to provide a seamless view. Hardware mounts were required to fit the new projectors, provide for quick replacement in the event of failure, and allow for mechanical alignment of the projectors' positions and orientations. The mount design had to be optimized for the ideal overlap between projectors, and minimized wasted image space and shadowing.

For the image generator, the decision was made to construct rendering nodes using commercial off the shelf (COTS) hardware with professional grade video cards that support external synchronization.

Software was required for IG control, image rendering and communication with the simulator, and for projector control and tuning. The rendering software was built upon a

combination of previous versions of miniSim™ rendering software, and software previously used to render auxiliary channels (extra displays not projected on the dome).

PROJECTOR SYSTEM

Projector system attributes such as resolution, brightness, contrast, latency, freedom from artifacts, overall visual impact and operating cost can all be improved by spending more money. Like most projects, the goal was to obtain the best possible system performance for the available funding.

Available Projector Types

A few models of 4K projectors had just been introduced, but they were too expensive for our budget in the quantities we required.

Traditional industrial projectors designed for use on motion base simulators were the obvious choice, but they were expensive and required proprietary software and costly support contracts. Affordable models would yield only a modest increase in resolution.

There were a large number of small consumer level HD projectors on the market. A few of them had low image latency and were favored by gaming enthusiasts. One strategy would be to modify these low-cost projectors to be rugged enough for use with motion. The product life cycles for consumer projectors are only one or two years at most. Therefore this type of system would need to accommodate multiple models of projectors as they are replaced with new models.

Many HD projectors with 1920 x 1080 resolution were available. In normal landscape mode, there would be no improvement in resolution over the old system, which had 1280 x 1024 resolution on the front projectors. The resolution could be nearly doubled with upper and lower projectors, but there would be a horizontal blend region near the horizon.

Another idea was to rotate the 1920 x 1080 resolution projectors to portrait mode, yielding 1920 pixels of vertical resolution, a substantial improvement. Most projectors would not allow rotation because of the hot arc-lamps that require landscape orientation for proper cooling. A number of LED and Laser/LED projectors were able to be rotated.

Many projectors could be ruled out for various reasons. Either they weren't rugged and stable enough, or the image latency was too high. Inexpensive LCD projectors generally had high latency times. DLP projectors were available with low latency, and were favored among gaming enthusiasts. Color banding artifacts with single chip DLP projectors was an issue. DLP projectors with three DLP chips would be ideal, but were expensive.

Comparison of Strategies

A spreadsheet was created to compare design strategies. A different design strategy was analyzed in each column of the spreadsheet. Each strategy used a different configuration of a specific model of projector chosen from the types listed above.

Each row of the spreadsheet contained a parameter to compare among the strategies. Some rows contained input parameters, such as model name of projector, number of projectors, projector lumens, projector resolution, etc. Some rows contained calculated parameters, such as pixels per degree of resolution, effective screen lumens, system purchase cost, bulb replacement and maintenance costs, etc.

After the various strategies were entered and analyzed in the spreadsheet, it became a simple matter for a group of stakeholders to compare the costs and benefits of the various strategies.

LED Projectors

LED illuminated projectors were not originally considered because of their reputation for lower brightness. However, with a number of strong advantages, they warranted a closer look. Advantages include:

1. No routine bulb replacements required

2. Lower power consumption and heat production

3. More reliable and longer life without hot light bulb

4. Smaller size and weight, thus mounting is easier

5. No rotating color wheel to wear out for single DLP projectors, because LEDs are flashed sequentially for color cycling

6. Ability to run in portrait mode for higher resolution and fewer wasted pixels

7. Stable and consistent brightness and colors, resulting in less frequent tuning [1]

8. LED dimming is available for low black level night scenes

9. More saturated colors are good for driving simulation, making it is easier to visually separate stop lights and tail lights from the background, which is often a bright gray sky

In consideration of these advantages, a few more strategies using LED projectors were entered into the spreadsheet. The strategies compared favorably to the aforementioned strategies. The two points of concern were low brightness

and image artifacts due to the single chip DLP.

Screen Gain

The last thing we did before starting projector evaluation was to consider screen gain, since this directly affects brightness. The dome screen in NADS-1 was originally painted in 1999 with a textured silver screen to increase the screen gain. The high gain was necessary with the low-brightness projectors available at the time. The screen was in good condition and did not need to be replaced. Perhaps the gain of the screen was high enough to allow the use of the dimmer LED projectors.

The high gain causes more light from the projectors to be directed toward the subject's eyes, and less stray light to be scattered around the room. Stray light lowers the contrast by contaminating other areas of the screen. The gain also guarantees the light seen by the subject comes from the projector, and not from other directions where stray light may be present.

To determine the gain of the screen, pieces of white paper with a gain near 1 were affixed to the surface of the screen. The screen was illuminated with a white field from one of the old projectors. Photos were taken of the screen and paper from the eye point and from off axis.
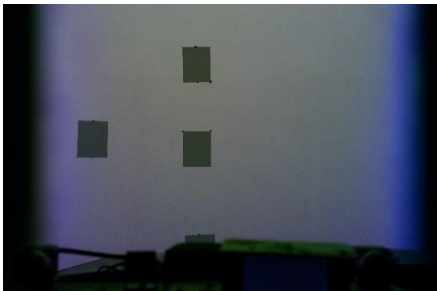

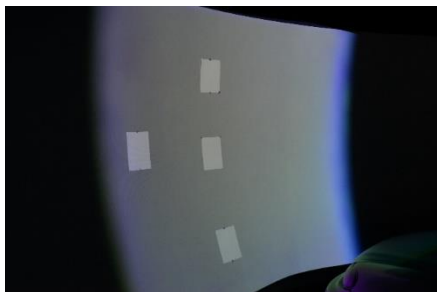**Figure 1 Photo taken from eye point**

Figure 2 Photo taken from off axis

In Figure 1, the white paper looks dark. This is because it scatters light in all directions according to Lambert's cosine law. The screen has a much higher gain, and directs much more light towards the eye-point.

Figure 2 shows the paper off axis from the eye-point. The paper looks much brighter because it scatters more light off axis, while the screen scatters less light off axis.

The screen gain was calculated from the pixel values of the photograph taken from the eye-point. The screen gain was calculated to be approximately 4.0. This means the screen intensity is 4.0 times what it would be if it were painted with a bright white matte finish. Without this gain, the LED projectors would not have been bright enough.

Projector Evaluations

Sample models of the various affordable projectors in the NADS-1 dome were reviewed. Subjectively, the LED projector reviewed was sufficiently bright. The contrast was very good and the dark level looked black. The review test was not ideal. The demo projector came with a wide angle lens. To fill the screen height it was necessary to place the projector much closer to the screen than its final installation.

The color banding artifacts caused by the single chip DLP in the LED projector did not seem too objectionable. Some reviewers noticed the bands when flicking their eyes back and forth and some didn't.

The bulb projectors were extremely bright, but their dark levels were also high, thus creating problems for night studies.

The Laser/LED projector was bright, but did not focus as sharp across a curved surface, and the greens seemed off color. It would have required modifications to the lens shift mechanism to make it stable enough for motion, and it had the highest latency.

Final Projector Selection

The selection was narrowed down to two LED projector models from Digital Projection (DP). DP recommended these models for use on a full motion simulator. Only one other competitor had similar products, but they were more expensive and did not yet have an established presence in the United States.

DP sells M-Vision projectors with 1920 x 1200 resolution which worked very well in our models. The 16:10 aspect ratio fit the screen shape almost perfectly when 16 projectors were used.

DP also sells projectors with 1920 x 1080 resolution for a significant decrease in price versus the 1920 x 1200 projectors. With 16 projectors the resolution and brightness would be reduced when the projector was zoomed out to cover the necessary width of the image area. Pixels at the

top and bottom of the image would be wasted.

To achieve the same brightness and resolution, 18 of the less expensive 1920 x 1080 projectors, versus 16 for the 1920 x 1200 models, would be required. This would require two more of everything, including IG channels, signal and control links, and mounting points, thus adding to the total system cost. Also, the 1920 x 1200 models had a few more features, including motion blur reduction.

In the end, we decided to purchase 17 of the more expensive M-Vision WUXGA LED with 1920 x 1200 resolution. In hindsight it was the right decision because the motion blur reduction turned out to be absolutely necessary. When it is turned off, and the subject turns a corner in the simulator vehicle, the trees in the background appear disturbingly smeared. We used 16 projectors in portrait mode with a resolution of 1920 x 1200. A 17th projector was purchased for a spare, which could also be used for off-line development.

Projector Acceptance Testing

A test procedure was devised for testing the projectors when they arrived. Each projector was closely examined for any quality problems. They all easily passed.

Each projector was also measured for brightness and color uniformity. The measurements were performed using a Konica Minolta CL-200 Chroma Meter. The meter was placed against the screen with the projectors placed at a calibrated distance and zoomed to a calibrated area. The lux measurement from the meter was multiplied by the screen area to determine the projector's output in lumens.

The results show excellent conformity between the projectors. Figure 3 and Figure 4 show the measurements of all 17 projectors.
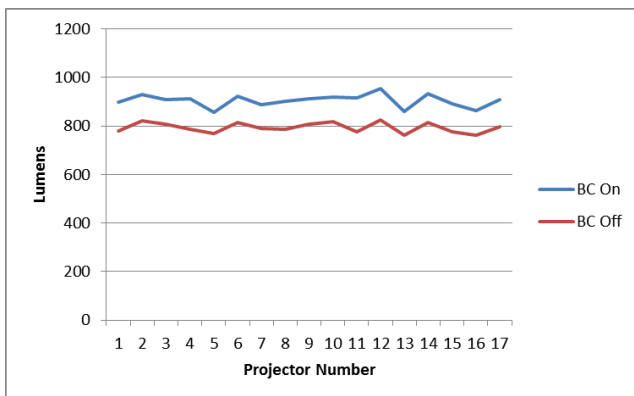

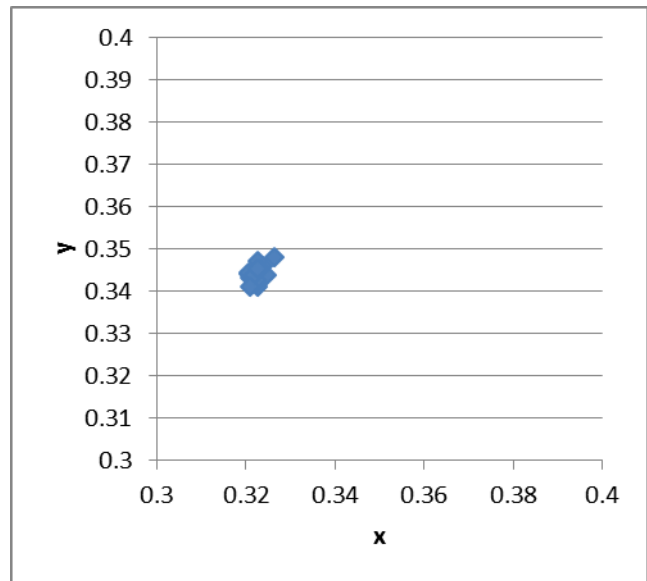**Figure 3 Projector output with Brilliant Color (BC) on and off**

Figure 4 White field color coordinates of all projectors, shown in CIE 1931 xy chromaticity space

System Layout, Geometry and Optical Design

The mounting position of the projectors is critical. This is due to the high gain screen. The brightest image is obtained when the angle of incidence (from the projector to the screen surface) is equal to the angle of reflection (from the screen surface to the eye point). As shown in Figures 1 and 2, the light intensity falls of rapidly as the angles change.

To determine the optimum position, a spreadsheet model was created to analyze the geometry of the projectors and dome. Inputs to the spreadsheet included diameter of dome, height of screen, height of dome equator above floor, height of eye point, height of projectors, projector radial setback from vertical centerline of dome, projector vertical angle, lens throw ratio, number of projectors, horizontal angular size of blend regions, projector aspect ratio, and vertical lens shift.

The model would calculate the percentage of projector pixels on the screen, the angles between the projector, screen and eye point for each pixel, and the variation in focal distance to each pixel as compared to the focal plane.

The projector position, angle and lens settings were adjusted in the model to increase the percentage of pixels on the screen. Figure 10 shows the illuminated screen area mapped onto the projector's raster. Approximately 90% of the raster is used. This high pixel utilization efficiency helps with screen brightness and resolution.

Finally, the angles and focal distances were checked to ensure light fall off and depth of focus were acceptable. A sample projector was placed on a ladder at the chosen location to verify the model was correct before designing the mounting structure.

Mounting System

The next step was retrofitting the projectors to the existing dome. The previous projector mounting system was designed for eight projectors of 4:3 aspect ratio oriented in landscape mode. Thus the move to 16 new projectors of 16:10 aspect ratio in portrait mode necessitated a complete redesign of the mounting system.

The requirements for the projector mounting system included the following:

- Safely support projectors weighing 550 lbs. total, along with ancillary equipment

- Rigid enough to prevent projector shake

- Allows quick replacement of a projector

- Adequate adjustment (roll, pitch, yaw) to accommodate all possible deviations from the 'ideal' mounting location

- Can be assembled onsite by a small crew

- Projectors orientated with exhaust vents on top

- Lens shift set to the far left (bottom in this case)

- No shadows on the opposite projector's frustum

- Overlap of about 2.5° at the top of each image

- Adequate space between the projectors and the dome ceiling for access and adjustment

A solid model was created of the dome, projectors, and their frustums to evaluate mounting locations. It quickly became clear that the possible locations that would satisfy the above requirements were few, and these matched very closely with the spreadsheet model.

A weldment was designed consisting of eight identical segments, Figure 5. The segments bolt together to form a ring that is attached to the dome in four places. Each segment contains three horizontal seamless steel tubes of 2 inch outer diameter within which two projectors are located. Commercial lighting clamps were used to attach the projector mounts to the tubes. The mounts incorporate a swivel plate for pitch adjustment, while the lighting clamps are slid horizontally on the tubes for roll and yaw adjustment, Figure 6. This approach proved to be simple and robust. The manual alignment phase was completed

very quickly with surprisingly good results, see Figure 8. The resulting structure is light and extremely stiff, with no noticeable projector shake.

Figure 5 Trial Fitting of Weldment

One significant problem was a lack of drawings of the original dome structure to provide landmarks to position the new structure in the center of the dome. CAD files were eventually located for the mounts installed in 2005 and using these, it was possible to design the new structure to utilize a few of the existing holes for alignment purposes.

New mounting holes were drilled in the fiberglass dome and the mounts through-bolted. Aluminum backup plates on the exterior of the dome were used to spread bolt loads over the dome surface. Aluminum sleeves were inserted into the holes to prevent the foam-core fiberglass structure from being crushed by the bolt clamp loads. Neoprene sheets were sandwiched between the plates and the dome surface to further aid in spreading the bolt loads as evenly as possible. The finished weight of the assembly is about 1250 lbs., roughly 200 lbs. less than the previous assembly.
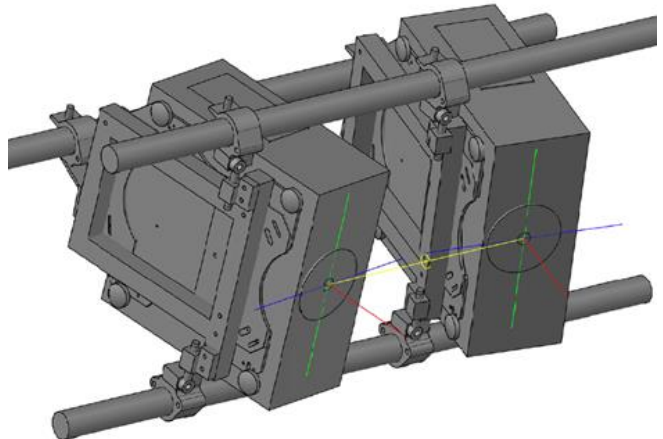

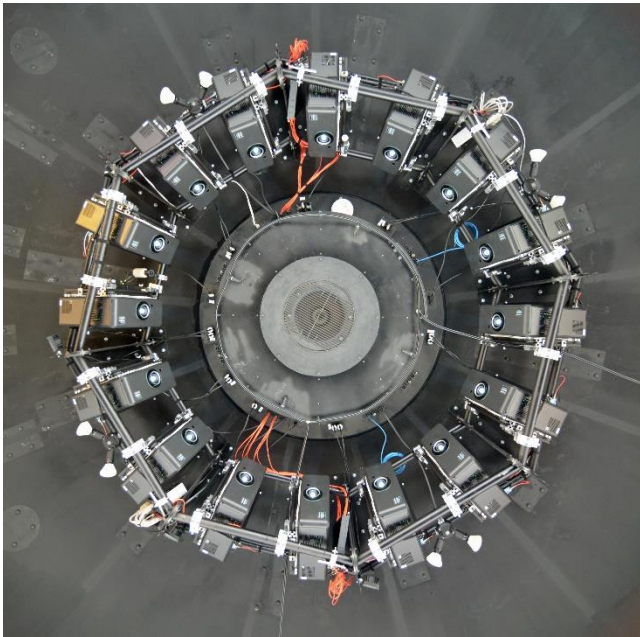
Figure 6 Projector Mount Design

Figure 7 Installed Projectors

Initial Alignment

A laser theodolite was used to provide reference points for aligning the projectors. The theodolite was placed at the eye-point and adjusted to the desired altitude and azimuth angles for placing alignment markers on the screen. Markers were placed along the horizon (eye point height) at the center of each image, and the middle of the edge blending regions. Likewise, markers were placed at the top and bottom of the screen, also at the center and edges of each image. A total of 96 markers were placed. With the aid of the laser theodolite, one person can place all the markers in under two hours.

For each marker, a patch of dark blue masking tape was applied to the screen over the laser dot. The masking tape was first tested on an inconspicuous area of the screen to ensure it would not leave any residue or damage the screen's surface. Then a white circle (a notebook paper reinforcement ring) was placed on the masking tape with the laser dot precisely located in the middle of the circle.

Test images were generated with custom software written in Visual Basic. The dome and projector geometry and desired lens settings were entered into the software. The test images consisted of pre-warped grids. They could be displayed on the projectors using a laptop PC. This was important because the signal distribution system from the IG was not yet completed.

For each projector, the vertical lens shift was adjusted to move the image all the way down to its limit. According to the spreadsheet model, this would give the highest pixel utilization and the flattest focus field. It also helped ensure the vertical shift would not move when the motion platform bumped in the vertical direction. Because the projectors are rotated 90 degrees into portrait mode, the vertical "down" direction on the screen is the horizontal "left" direction on the projectors. The horizontal lens shift adjustment (the projector's vertical) was adjusted to the approximate center of its range.

Each projector was mechanically aligned using the roll, pitch and yaw adjustments provided by the mounting system. The lens zoom and focus were also adjusted at the same time. Finally, the horizontal lens shift (the projector's vertical) was fine tuned to place the vertical centerline of the test image through the center target on the screen. The mechanical alignment did not need to be perfect, as it would be fine-tuned later with tuning software. Figure 8 shows how close the grids between projectors matched with mechanical tuning alone.
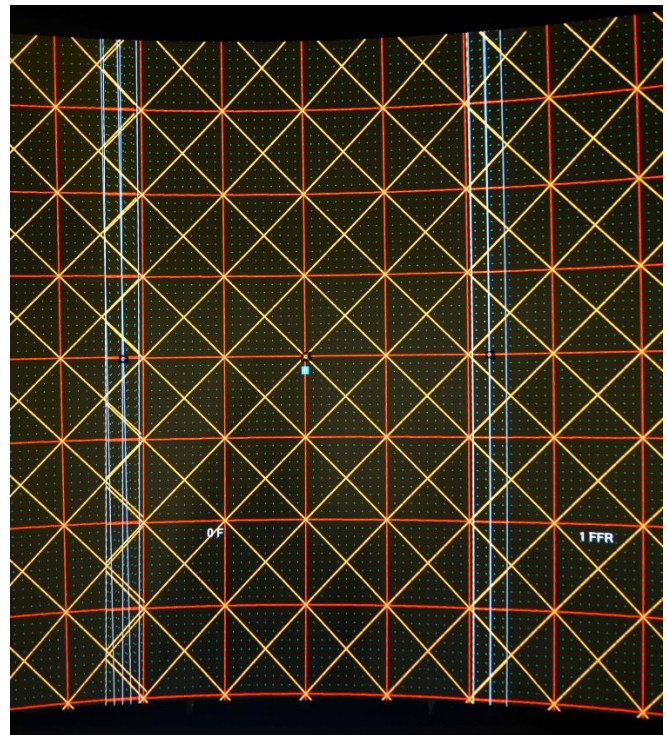

Figure 8 Tuning grid test pattern after mechanical alignment

Projector Tuning Software

With the projectors placed, the next step in the display side of the imaging system was to develop software to create a

single seamless image from 16 unique projectors.

Image warping and blending software was implemented on the image generator (IG). The projector tuning software is used interactively by the tuning technician to produce the files used by the warping and blending software. Currently the tuning is performed manually. The file interface used between the tuning software and the warping and blending software lends itself to future implementation of auto tuning software.

Geometry Tuning
Warping is performed on the IG using a program that calls the warping functions in the NVAPI. NVAPI is an API provided by NVIDA that can take geometry data as an input to setup the display driver to provide warping [2].

The geometry data contains a list of input points paired with output points. The input points specify locations on the IG's image plane. The output points specify locations on the projector's raster.

Figure 9 shows the input points plotted on the IG's image plane. The curves at the top and bottom represent the top and bottom of the dome's screen. Figure 10 shows the output points plotted on the projector's raster. The points are spaced further apart at the top because the projectors are closer to the top of the screen.

An initial list of input and output points is calculated from the geometry of the dome, projectors, and nominal lens settings. It is the same geometry used to generate the pre-warped test patterns for projector alignment.

The geometry fine tuning works by moving the output points in order to align points in the test pattern with the markers on the screen. The points are moved using commands from the tuning technician. The technician views a test pattern on the screen and enters a command to stretch the pattern so the points in the test pattern map onto their correct locations. The correct locations can be the markers on the screen or points in the blending regions where the neighboring projector's points overlap.

After each command is entered, the tuning software calculates a new geometry and loads it into the IG warping program. The test pattern is re-warped as a result, and the technician quickly sees the results of the command. The technician chooses the next move and repeats the process until all the points in the test pattern map onto their proper locations.

Currently the tuning commands are entered into a text file which is interpreted by the tuning software to generate geometry.
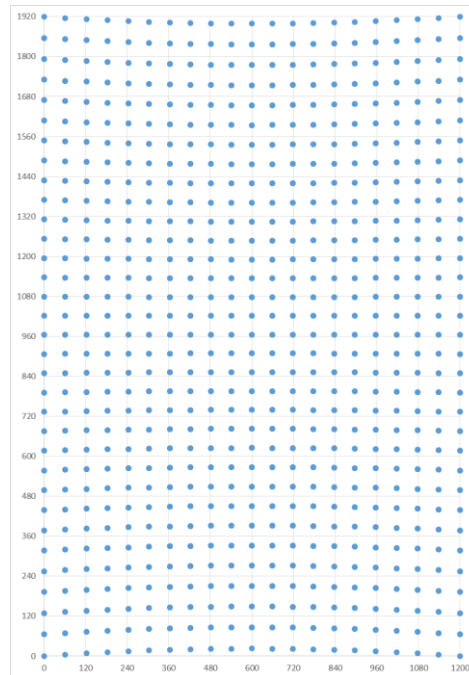

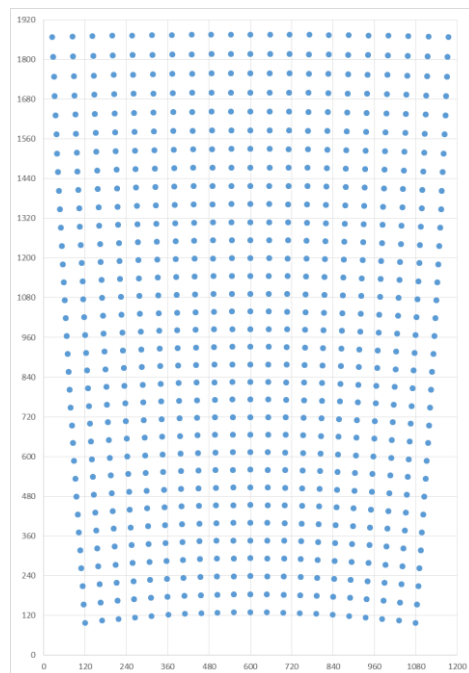**Figure 9 Geometry input points mapped onto IG renderer's image plane**

Figure 10 Geometry output points mapped onto projector's raster

Each tuning command specifies how the geometry is stretched. Each command consists of a code and a value. Command codes beginning with "h" stretch the points in the horizontal direction, and codes beginning with "v" operate vertically. The value field in the command specifies how much stretching is desired. The units are in pixels. For example, the command "hs 3.5" increases the horizontal size by 3.5 pixels. Table 1 shows a list of the commands.

Command Code	Function
rot	Rotation
hp, vp	Position
hs, vs	Size
hl, vl	Linearity
hsk, vsk	Skew
ht, vt	Trapezoid
hc, vc	Curvature
hb, vb	Barrel

Table 1 List of tuning software commands

Geometry tuning commands are entered into a text file. The geometry output points are modified by each command in the order it appears. Commands may be entered more than once. There is an interaction between the commands depending on the order they appear in the file, so an iterative approach is necessary while tuning.

Because of the accuracy of the original geometry data, and good mechanical alignment of the projectors using the test images, only a few small changes in the geometry tuning file are usually required. Listing 1 shows a typical geometry tuning file.

```
vp -4
rot -.3
ht 8
hs 2
hp 1.5
vs 8
```

Listing 1 Typical geometry tuning file

Figure 11 shows the blend region between two projectors when geometry tuning is complete. The orange squares are 5 degrees on each side. The green dots are spaced by 0.5 degrees. The vertical white lines show the left edge, center and right edge of the blending region, which is 2 degrees wide.

When the green dots are aligned, and the lines are straight as they pass through the blending region, the geometry tuning is complete.
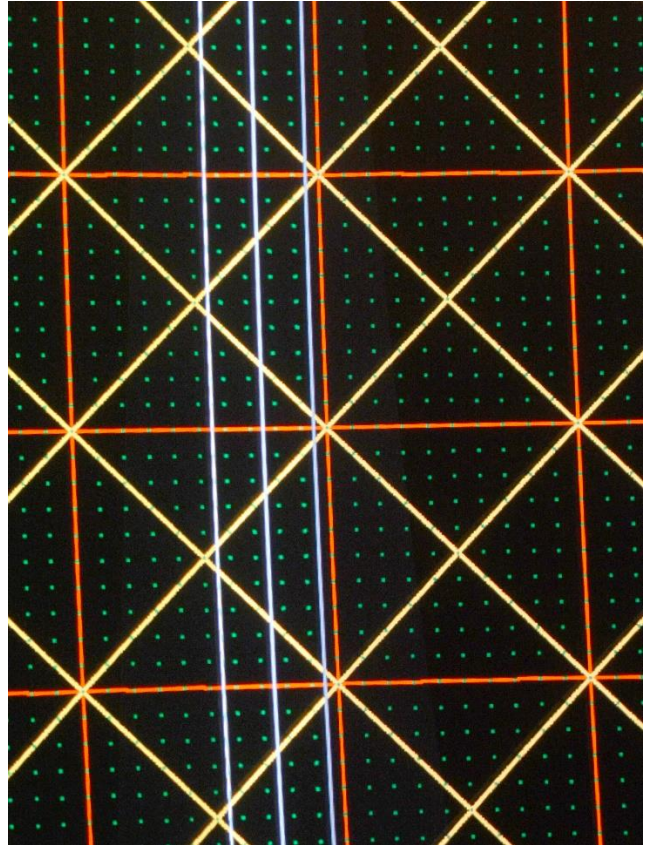

Figure 11 Blend region after geometry tuning

Color Tuning
Color tuning includes adjustment of white RGB levels and monochrome black levels. The output of the color tuning program is a text file that specifies these four parameters for each pixel location of the renderer's projection of its frustum.

The tuning software calculates the output file in response to commands from the tuning technician to accomplish the following goals:

1. Perform edge blending

2. Match the overall white level between projectors, and across the image for each projector

3. Match the RGB color balance between projectors and across the image for each projector

4. Adjust the black level between the projector overlap regions, to conceal the wedges

5. Mask the top and bottom of the images, where the image goes off the screen or strikes the vehicle

Edge blending

The process starts with a template output file with only the blending regions encoded. The R (red), G (green) and B (blue) values are 1.0000 between the blend regions, and the black level values are all set to 0.0000. The blend regions are set to go from 0.0000 to 1.0000 across the blending region using a sine squared function on the left edge, and a cosine squared function on the right. This guarantees perfect blending, provided the geometry is correct, because of the identity $\sin^2 x + \cos^2 x = 1$.

Tuning text file

The input to the color tuning program is a text file. An example is shown in Listing 2. The tuning technician enters values iteratively while observing the results.

```
Left
0       927
479     972
959     1010
1439    1038
1919    1058

Right
0       269
480     222
960     187
1440    160
1919    142

Bottom
0       0
0       1199

Top
1919    0
1919    1199

Dither  .0002

TopRight      1.015   0.990   0.990   0.00035
TopLeft       1.010   0.990   0.990   0.00040
BottomRight   1.015   1.000   0.995   0.00040
BottomLeft    1.010   1.000   1.000   0.00080
```

Listing 2 Color tuning file

Color balance

Because of the single chip DLP design of the projectors, all colors are modulated by the same imaging device, and are therefore extremely consistent. There is a small variation between the colors and intensities of the individual projectors. There is also a variation between the top and bottom edges, and the left and right edges of the screen. This variation is different between projectors.

The last four lines in the tuning file specify the R, G, B and black levels for each of corner of the image. The R, G and B values are adjusted with a light gray test image until all the images are the same color of white, and the edges between neighboring projectors match from top to bottom.

Black level correction

The projectors have a contrast ratio of about 2000:1. Where the images overlap, the black level intensity is doubled, and the resulting contrast ratio is 1000:1. In a dark scene, the overlap regions are clearly visible. Figure 12 shows the elevated black level in the overlap regions.
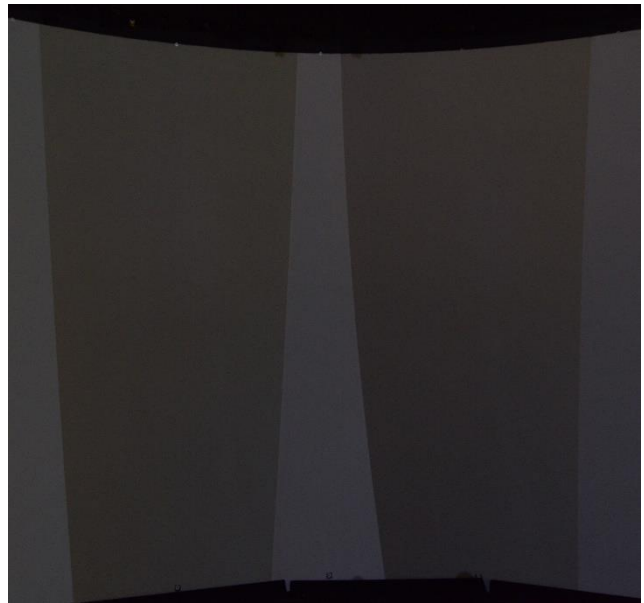

Figure 12 Photo of elevated black level in projector overlap regions

Black level correction is used to conceal the overlap regions. A small amount of black level is added to the pixels in the non-overlapping regions, so the black level matches the overlapping regions. The fourth value in each of the last four rows of the color tuning file contains the amount of black level to be added to each pixel between the overlapped regions. The overall image will have a resulting contrast ratio of 1000:1.

The geometry of the overlapped regions is specified for the left and right edges at the top of the color tuning file. The lists of points specify the shape of the overlap using piecewise linear interpolation. If the horizontal position of the point is too far towards the edge, a faint white line appears. If the position is too far away from the edge, a faint dark line appears. Generally a faint dark line is less noticeable to the subject. The tuning technician works close

to the screen to minimize the faint line. It is always visible close to the screen, but virtually undetectable from the subject's view at the eye point.

Figure 13 shows the overlap region with black level correction applied. These photos were taken with the camera exposure set to 1 second, f8 aperture, and ISO3200 sensitivity.
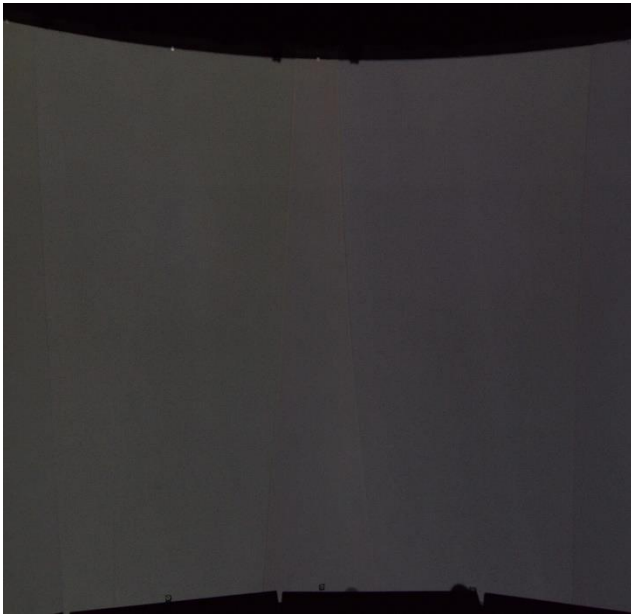

Figure 13 Photo with black level correction applied

Masking
A small amount of light from the projectors projects onto the black area above the screen, and onto the simulator cab. The shadows cast by the cab are not visible to the subject, because the shadows are occluded by the bodywork of the cab from the subject's perspective. The problem is that light from the projector is reflected off the windshield and rear window, and reflects undesirable images back onto the screen.

The "Bottom" and "Top" sections of the color tuning text file allow the tuning technician to define a border to mask out the image. The list of points is interpolated piecewise linear, just like the "Left" and "Right" sections of the file.

Projector movement or replacement
If a projector is moved or replaced, the geometry and color tuning procedures will need to be performed for that projector. The color tuning will also need to be performed for the neighboring projectors. This is because any movement will change the shape of the overlap regions. Even slightly adjusting the zoom or focus of a projector

will alter the shape of its raster.

Projector Control Software

The next step in the development of the image display system was the development of control software for the projectors. The M-Vision projectors are equipped with serial ports for the purpose of remote control. The Projector Control program can send commands to the projector, and receive status and other information from the projector.

The serial ports can be daisy-chained from one projector to the next, but in this case the Projector Control program cannot receive data returned by the projector. Therefore we decided to build hardware to distribute a single PC serial port to all 16 projectors, so they could be selected one at a time. This hardware will be described in the next section.
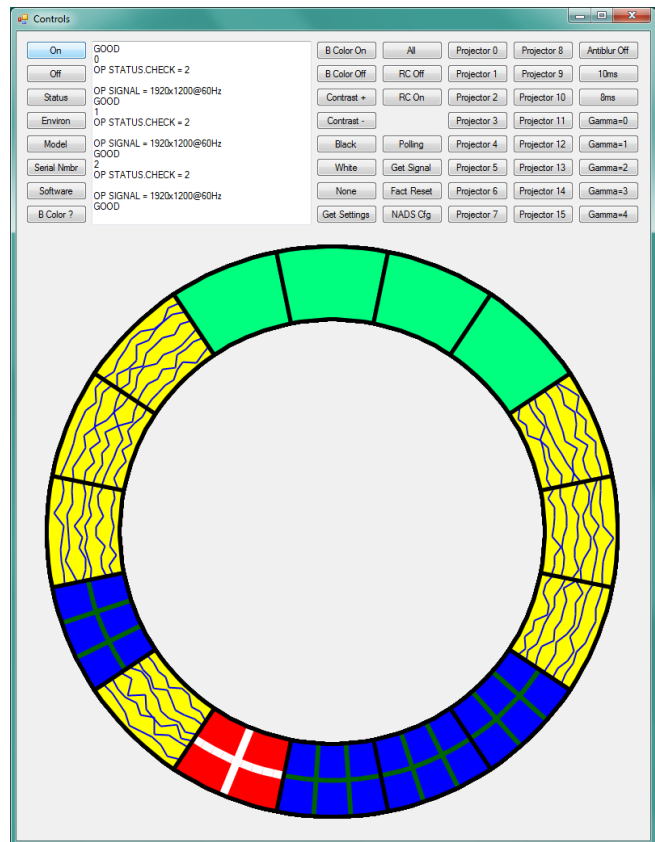

Figure 14 Projector Control software shows status changes of projectors as they are being turned on

The Projector Control program continuously monitors all the projectors, one at a time. First it sends a code to the Serial Distributor hardware to select the projector, and then sends a command to get the status of the projector. Then it repeats the process for each of the other projectors. The

display shows colors and patterns graphically to indicate the status of each projector.

Figure 14 is a screenshot showing the projector status screen from the Projector Control software. Solid green shows a projector is turned on and receiving a good signal. Yellow with squiggly lines shows the projector is receiving a bad signal, usually because the GPU is not properly synchronized. No color shows the projector is turned off. Other colors and patterns show errors or intermediate states while the projectors are turning on and off. The simulator operator can tell at a glance that all projectors are functioning properly.

The Projector Control program has buttons to control all the functions of the projectors. Button commands are typically sent to all projectors, but specific projectors can be sent commands individually. In normal operation, clicking the "On" button turns all the projectors on. Clicking "Off" turns all the projectors off.

There is a button to reset all the projectors to their factory default configurations. This feature makes it easy to know that all projectors are set exactly the same.

There is also a button to set all the projectors to the standard NADS configuration. This button runs a script that first resets all the projectors to their default configurations, then performs various other functions, for example to select the correct gamma, turn on the motion anti-blur, and turn on the "Brilliant Color" function for a brighter image. This way it is known that all projectors are set to the required settings for the experiment.

All 16 projectors are typically set exactly the same. They are not individually adjusted for contrast, brightness or color balance. All tuning adjustments are performed with the tuning software on the IG. This is made possible because of the consistency between all the projectors. If it ever becomes necessary to store different configurations for different projectors, the Projector Control program can be updated with that functionality.

The Projector Control program runs on the desktop of the IG control PC. It occupies the left half of the screen. The IG Control program runs on the right half of the screen. A projector tuning technician will use a laptop in the NADS-1 dome to remote into the IG control PC in order to control the projectors and the IG at the same time while tuning.

Control and Video Signal Distribution

The NADS-1 simulator motion base rides on a large x-y track system to create lateral accelerations, requiring cabling to be flexible and long. Fiber optic cable is used for nearly all signals between the moving dome and the stationary control rooms. A number of cables containing 12 fibers each were already routed between the IG location and the dome. The old projector system required more fiber channels than the new one. There was already enough capacity in the original cables, including plenty of spare channels.

Fiber Patch Bays
Fiber patch bays were installed at each end of the existing multi-fiber cables. This allows for ready access to the cable channels, for rerouting failed channels, and for connecting new equipment as needed. It also provides for a much neater installation.

Video Fiber Converters
The new system uses Gefen DVI FM-1000 DVI to Fiber converters. Each projector needs only one fiber. The DVI to Fiber converter is plugged directly into the DVI-D connectors on the GPU cards. The Fiber to DVI converters are plugged into 8 inch adapter cables that convert the DVI-D signals to the HDMI connectors on the projectors.

The baby blue fiber converters can be seen in Figure 16 and Figure 19.

Serial Port Distribution
Two fiber channels are used for the serial port link between the IG control PC and the projectors.

As previously discussed, custom made Serial Distributors were fabricated to control the serial port of each projector individually from a single serial port from the IG. Two Serial Distributors are daisy-chained together. Each one has eight serial ports for the projectors.

The Serial Distributors also provide power to the Gefen Fiber to DVI converters. This eliminates the need for the wall transformers which came with the converters. The power is carried over unused pins in the serial cables. The serial cables are custom made, to provide the barrel connector at the projector end to plug into the converters.
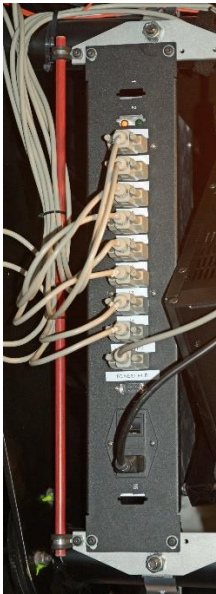
Figure 15 Serial Port Distributor

Figure 16 Projector Wiring Detail

IMAGE GENERATOR (IG)

The development of the NADS-IG was developed concurrently with the effort to replace the projectors.

The NADS-IG was constructed out of six nodes (computers), each containing two NVidia K5000 graphics cards and one Quadro 600 video card. Four nodes drive four projectors each, with one node being used to provide operator displays (overhead view and 360 degree view). The remaining node is used for auxiliary displays, such as LCD display mirrors, Forward Looking Infrared (FLIR) displays, or backup camera displays for the driver. An additional node was built for NADS-2, which is a fixed based simulator with only a forward view. The Quadro K5000 cards are used to drive the projectors, while the Quadro 600 is used for the desktop. The auxiliary displays are changed on a per experiment basis.

Figure 17 shows the interconnection between the IG nodes. The 5 nodes that distribute the video to the dome are located in the same rack, while the control room render node is in the control room.

The NADS-IG also includes a small server that acts as the IG Control. This is used for system configuration, system monitoring, and operator control.
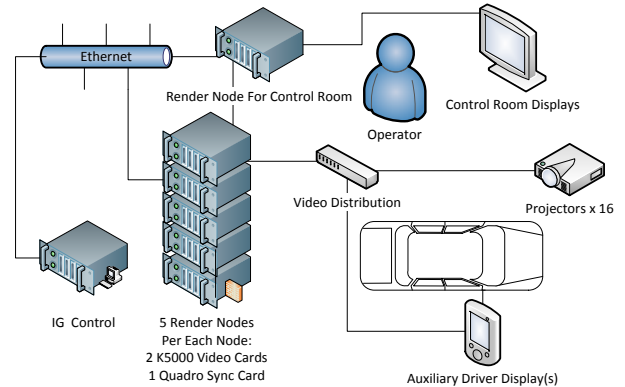

Figure 17 Image Generator Wiring Diagram

The rendering software utilizes Open Scene Graph (OSG) for performing the rendering. Most of this work was taken from previous efforts on the NADS miniSim™. Open Scene Graph was modified to set the GPU affinity mask. This was necessary to match up the GPU with the rendering context (screens to video cards). Windows 7 by default sends the GPU commands to the most powerful GPU on the system, and the results are copied to the second GPU. Setting the GPU affinity mask can be used to work around this in order to balance the load between the two K5000 cards in each render node [3]. DiGuy^tm was also integrated to greatly improve the quality of pedestrians.
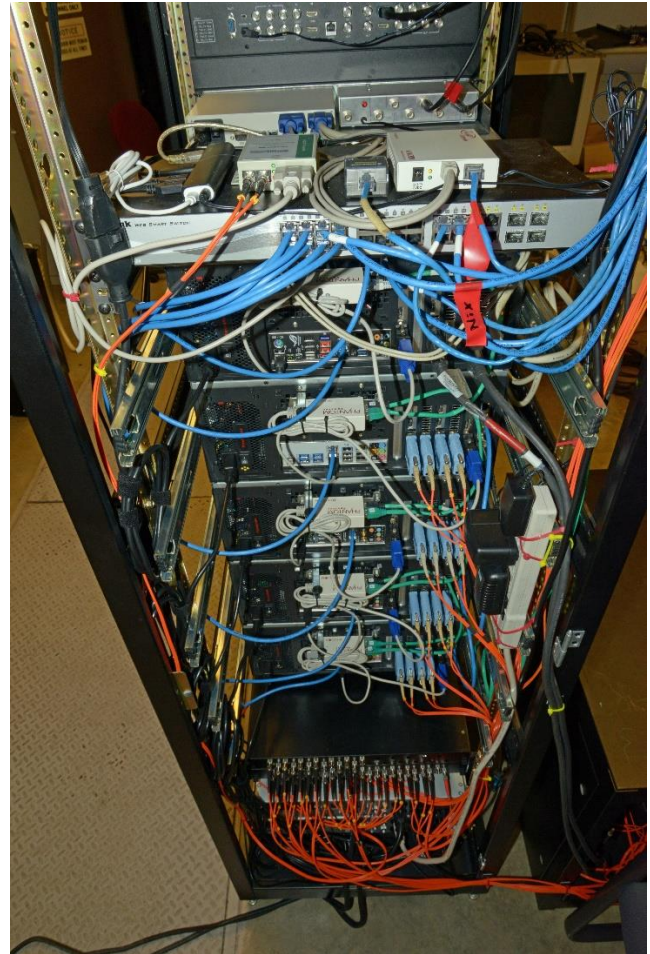
Figure 18 Image Generator Front

Figure 19 Image Generator Rear

The NADS-IG is connected via an Ethernet connection to the Scenario Control Subsystem in the NADS Simulator. All of the simulation nodes that drive the simulator are connected to each other via SCRAMNET. SCRAMNET is a reflected memory system, where each SCRAMNET card has physical memory on it. Writes to this memory get propagated over the network, which uses fiber optic cables. SCRAMNET also has an interrupt capability, where a single node can fire an interrupt on every system on the network. This is used by the Frequency Based Scheduler (FBS) to perform frame generation. At the start of every frame (signaled by the FBS) each subsystem reads data from the SCRAMNET card. Once a frame has been completed, each system writes the data back out to the SCRAMNET card where it gets broadcast to the rest of the network.

The image generator is not on the SCRAMNET network itself. The Scenario Control (NIX) system, which is on the

SCRAMNET, works to coalesce a single simulation state from itself and other systems, and to send the state information via the image generator communication system, IGComm, to the IG nodes. The simulation state is conveyed to the IG nodes as a series of commands to create new vehicles, update vehicle positions, move the eye point, and so on.
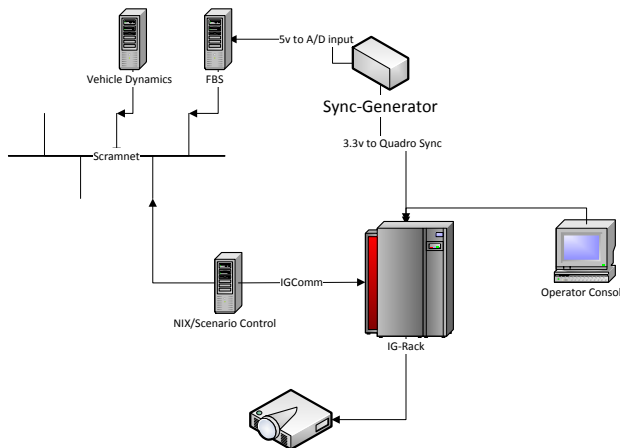

Figure 20 NADS-IG Communication Diagram

Synchronization

All of the subsystems in the NADS-1 simulator, including the IG, must be synchronized to keep a consistent graphics state and to synchronize motion queues with visuals. Failure to synchronize can cause jitter in dynamic scenario elements, eye point jitter, vertical tearing at blend regions, and mismatch between visual and motion cues. Jitter can artificially increase changes in vection that can cause simulator sickness [4]. Lack of synchronization can also lead to the motion system and visual system not being in agreement (the optical flow from the image generator does not match the motion system). Disagreements between vestigial (motion) and visual cues can lead to simulator sickness [5].

The NVIDIA Quadro Sync card was utilized to obtain synchronization between the multiple IG nodes and the NADS simulator. The Quadro sync card takes external house sync as an input. The FBS system has an A/D card which can be triggered from an external signal. Given this, we used an external signal generator to drive both the FBS system and the Quadro sync system. The FBS system in turn generates 3 intermediate frames to drive dynamics and other systems that run at 240 Hz. The image generator and projectors run at 60 Hz. Figure 20 shows the interconnection between the simulator and the IG. A number of Quadro Sync cards can be daisy chained together. Only the first card receives the external sync signal.

The Quadro Sync card has a setting for an offset applied to the external sync signal. The offset is configured to delay the IG by 2 ms, allowing enough time for the scenario control system to send data to the IG before the IG begins processing the next frame.

Sync Generator
Broadcast quality sync generators that meet the accuracy requirements of the NVIDIA cards are expensive and complicated, and provide many unnecessary functions. They also do not come with the required 5V and 3.3V outputs needed by the FBS and Quadro Sync cards, and would need to be converted.

Therefore, a simple 60 Hz hardware sync generator was designed and constructed as part of the IG. It consists of a PIC microcontroller and stable 24 MHz crystal oscillator. A 5V output was provided to be sent to the FBS sync input device. A 3.3V output was provided to be sent to the first NVIDIA Quadro Sync card. Other outputs were provided for future use. The output frequencies, polarities and phase delays can be chosen by changing the firmware running on the PIC microcontroller.
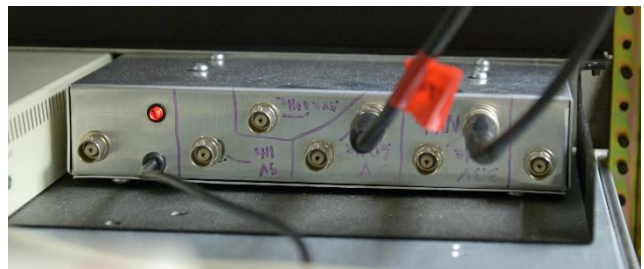

Figure 21 Sync Generator

IGComm

IGComm is a software library that is designed to handle communications between the IG software and NADS. NADS has one system responsible for scenario control called NIX. Both NIX and the IG utilize IGComm. IGComm is responsible for constructing a single simulation state, and communicating this with the IG. The simulation state contains the location of the subject, location of all the dynamic objects, and any other relevant data about the visual scene.

The NADS-IG was based on an older system that had been used at NADS for years to render auxiliary channels in the NADS-1 (such as mirror displays, head unit with FLIR,

etc.). NIX would communicate with this Auxiliary channel, as well as with the old Quantum3D IG using the Common Image Generator Interface (CIGI). This older system had a fully functional communication system; however it only supported the remote control of one auxiliary channel at a time.

We decided since we had a fully functional system for packing, unpacking, and reassembling a graphics state, we would adapt our existing system to a fully distributed system. This way we could support multiple render nodes. In respect to the Open Systems Interconnection (OSI) 7 layer model, NADS had a fully working application layer and presentation layer. What was needed was a session layer that supported connecting multiple render nodes, and a transport layer that supported broadcast based communication. To achieve this we split the communication system up into three streams: Command Stream, Advertisement Stream, and Real-time Data stream.

Advertisement Layer
The advertisement layer provides status information about each IG node. Each program running on the IG broadcasts its state including its command port, performance statistics, and other status information. Each advertisement fits within a single UDP packet, with the UDP packets being sent out at around 10 Hz. NIX uses this information to establish connection with the IG nodes, and the IG Control software uses this for status information.

Command Layer
The command layer provides a point to point link from the NIX (which manages the simulation state) to each IG node. This layer provides a command and control functionality. NIX establishes a connection with each IG node based on information provided by the advertisement packet. Each instance of the rendering software can only host one command connection at a time. NIX can host up to 32.

Real-time Layer
The real-time layer utilizes UDP broadcast. It provides the graphics state during the running of the simulator to each of the individual nodes. It packages the graphics state (expressed as a series of commands) into individual packets, broadcasts them from NIX, and reassembles them on the individual IG nodes. This layer provides rate control and reliability checks for each individual command. Each command has a CRC code generated for its header. The actual commands themselves were taken from the original communication system, and mostly unmodified.

Being There
Being There is a utility developed to act as a surrogate for NIX. Like NIX, it also utilizes IGComm. It is used for testing the IG software. It can passively listen on the IG network, and record a replay file of the real-time communications. It can load and playback replay files, and allow an operator to control the eye point. It is also useful for displaying pre-recorded simulator scenery on the projectors without running the whole simulator, to facilitate tuning.

Warping and Blending Software
As previously discussed, the NADS-1 screen is spherically shaped and requires warping of the image. Blending is also required where the projector images overlap.

For the warping, we used the NVAPI, which takes in geometry data to perform the warping [2]. A simple application was written to read the geometry data from the tuning software, and load it into the NVAPI. This required no direct modification of the IG software.

Blending Shader Function
A fragment shader function was written to implement blending and color correction. This function is appended to the end of the fragment shader for the final rendering pass by the IG's shader composition system.

The function first clamps each pixel to an RGB value between 0 and 1. This ensures that values exceeding maximum brightness (1.0) will not show up unclipped in the blend regions.

Next, an inverse gamma function restores the pixel values to a floating point linear representation. The addition and multiplication operations are then performed in linear space. Finally, the gamma function is reapplied and the result is dithered. Dithering is necessary because the output values are quantized into 8-bit integers. Without dithering, quantization bands would form in the dark areas of the image.

The system uses a gamma of 2.2 throughout, which matches normal PC monitors. The projectors have a setting that uses this gamma.

The input values for the shader function needed to be higher than 8-bit resolution, so a 16-bit offset binary coding was used. The 16-bit integer range of -32768 to +32767 was mapped onto a floating point range of -2.0 to +2.0. Even this step required much effort, because base 255 math was needed. (The NVIDIA processors convert an 8-bit value of 255 to a floating point value of 1.0.)

The shader function is implemented as the final step in the rendering process. The warping function is then implemented between the desktop and the display devices.

IG Control
The NADS-IG Control system's primary responsibility is to

provide operator control and interface for launching NADS-IG nodes, and monitoring health status of each IG node.

The NADS-IG control system's design goal was to create a rapidly-reconfigurable system that could dynamically grow over time, leveraging modern hardware. The software was built using Node.js, using Socket.IO to facilitate real-time bidirectional communication between the IG Control PC (IGC) and any number of IG render node host PCs.

Each render node host PC runs a "client" script that connects it to the main control script on the IGC. The client script digests captured events sent from the IGC to control applications and system functions on its respective host, and to report status and output data back to the main control script.

The IGC hosts the main control script and web-based control panel. The IGC main control script serves as the communications hub between all render node hosts and any connected instance of the main control panel or specialized control surface. It monitors all aspects of system health and connection status of connected nodes. It also digests UDP status broadcasts (part of the advertisement system from the IGComm) from each renderer, and transmits instructions to render node hosts from control surfaces. It has the ability to stream all of the associated state and mode data to a back-end database for diagnostic post analysis, as well as all connected control panel instances.
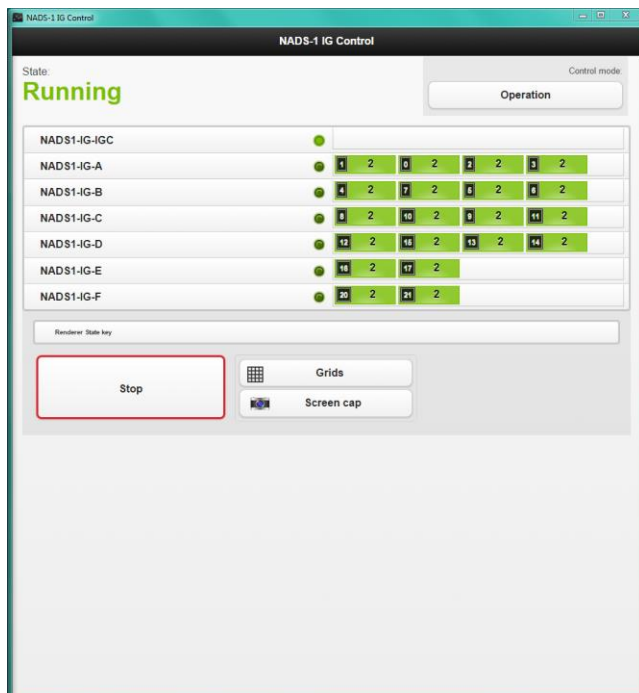

Figure 22 NADS IG Control Panel

The main control panel is an HTML5 web application built to be as client device agnostic as possible. Connected to the main control script, it works as a single control interface for the use and real-time health monitoring of all connected IG systems and processes. It can be used on any modern browser connected to the IG, whether the client is a workstation, tablet, phone, or other device. The main control panel also performs tasks such as controlling power states of IG systems, starting and stopping render node processes, displaying projector tuning grids and patterns, copying IG executables from a main repository to render node hosts, copying master render node host client scripts to render node hosts, and executing arbitrary interactive command line calls to any connected node. Higher-level abstracted tasks include taking a full system "screenshot" that gathers images for a point-in-time view of all rendering processes. All tasks can either be targeted to a specific host, or broadcast to the full IG system or any subset groupings of hosts.

RESULTS

Figure 24 shows a photograph of a night time driving scene with the new system. This picture was taken at the driver's eye point and contains at least one blend region. Compared to Figure 23, a photo of the old system, the new system has much higher contrast, more accurate colors, and is much clearer.

After the upgrade, NADS-1 experienced a major improvement in the realism survey scores. The realism scores were taken from subjects during their post drive interviews. The scores relating to the visual system show a 36% increase. Figure 25 shows the improvements. The pre-upgrade and post-upgrade drive studies both used the NADS impairment scenarios. These studies used the same visual database, with only slight modifications to the scenarios [6]. The pre-upgrade scenario involved cannabis and alcohol impaired driving, while the post-upgrade study involved drowsiness. The age group for the pre-upgrade study was 21 to 42, and 21 to 34 for the post upgrade study.

Figure 23 Photo of night time scene using old system

Figure 24 Photo of night time scene using new system

Figure 25 Simulator Realism Survey Results (0 completely unrealistic, 7 completely realistic).

Another area where NADS saw major improvement was with decreased energy usage and better thermal management. The 16 new LED projectors produce much less heat than the 8 old arc lamp projectors. The old system (a combination of BARCO Sim 6 and Sim 6 Ultra) had a combined maximum power rating of 7600 W [7] [8] versus 5280 W for the new system [9]. The air conditioning system would barely keep up with the old projectors, but runs less than 50% duty cycle with the new ones, suggesting a greater power savings than the maximum power ratings would indicate.

The latency of the new IG was measured with the old projectors. A square wave signal was injected into the gas pedal input of the cab, and the renderer was programmed to set the screen to white or black accordingly. The square wave was connected to one channel of an oscilloscope, and a photo diode was connected to the other. An average time delay of 72.8 ms was measured. Unfortunately we have not yet been able to measure the latency with the new projectors, but we expect similar results.
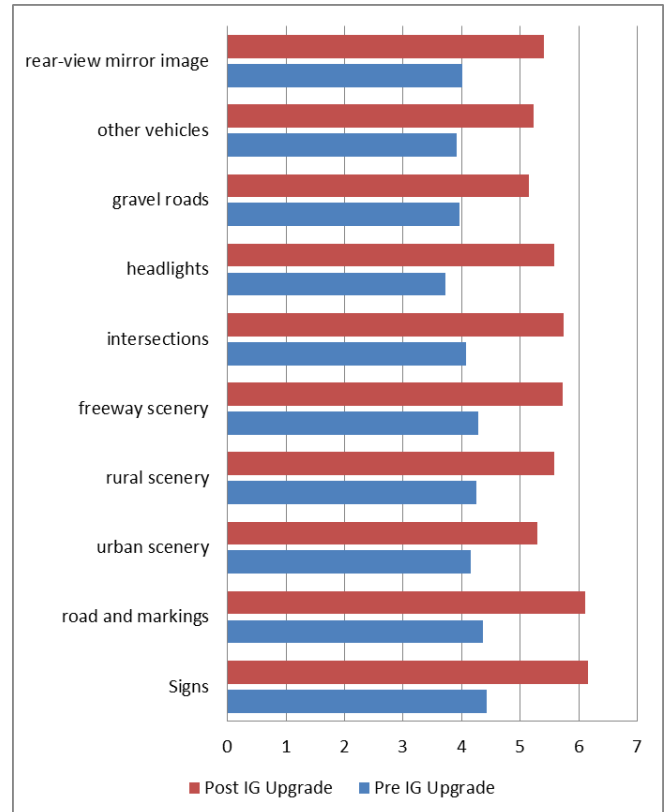
The old system had a resolution of 26.7 pixels per degree in the front channels (lower in side and rear). The new system has a resolution of 42.7 pixels per degree at the horizon in all channels.

The old system used optical edge blending. Masking plates inside the projectors were adjusted to match the edges. It was never possible to make the blending regions disappear. With the new system and tuning software, the blending regions are virtually unnoticeable as viewed from the eye point, as shown in Figure 24.

CONCLUSIONS

Overall NADS was able to construct a system at reasonable cost that fulfilled its needs. The new projection system greatly improved sign legibility and perceived visual quality of day and night scenes. The new system is much easier to use, and requires less time for operation, tuning and maintenance tasks. Because the software was developed in-house, NADS is free to make changes as needed without relying on external vendors.

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In the future we plan on adding auto tuning of the projectors, and continue enhancement of the rendering system.

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David Heitbrink is a Software Engineer at the National Advanced Driving Simulator. He is responsible for maintaining many of the software systems that run the NADS simulator, including scenario control system, scenario authoring tool set, and many other smaller systems. He was the lead software developer on the effort to design a new image generator for NADS, as well as a new audio subsystem a few years before that. Mr. Heitbrink received his Bachelor of Science in Computer Science and Engineering, and his Master of Science in Engineering at the University of Toledo. He joined the staff of NADS in 2005.

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