Ambient-Aware Aperture Optimization

1 Introduction

DLP projector brightness and contrast are inversely related by the system f-number. Light throughput is inversely proportional to the f-number of a projector. As the f-number decreases, more light is delivered to the DMD and imaged through the projection optics and onto the screen. Conversely, contrast decreases when the system f-number is decreased, as the larger aperture allows more stray light to enter the projection lens and make its way to the screen. If the f-number is raised, which limits the collection of stray light, the black level is lowered and contrast is increased. With fixed system apertures, the optics designer must choose a static tradeoff between contrast and brightness. An optimal system would tune the aperture stops according to the ambient light conditions, enlarging the apertures for high brightness environments and closing them for dark ones. This paper will elaborate on the relationship among light throughput, contrast, and f-number for DLP projectors. Additionally, it will discuss the new Projected Image System Contrast Ratio (PISCR) ANSI standard and its importance for image quality evaluation. Finally, it will propose a few optical architectures and algorithms to achieve optimal aperture stop settings for given ambient light conditions.

2 Light Throughput, Contrast, and F-Number

A projector's contrast, light throughput, and f-number are directly related to the aperture stops in the system. Typically, there are two aperture stop locations. One is located in the illumination path, between the light source and the DMD, and the other is located in the projection path, between the DMD and the imaging optics. The figure below illustrates typical aperture stop placement for a DLP system.

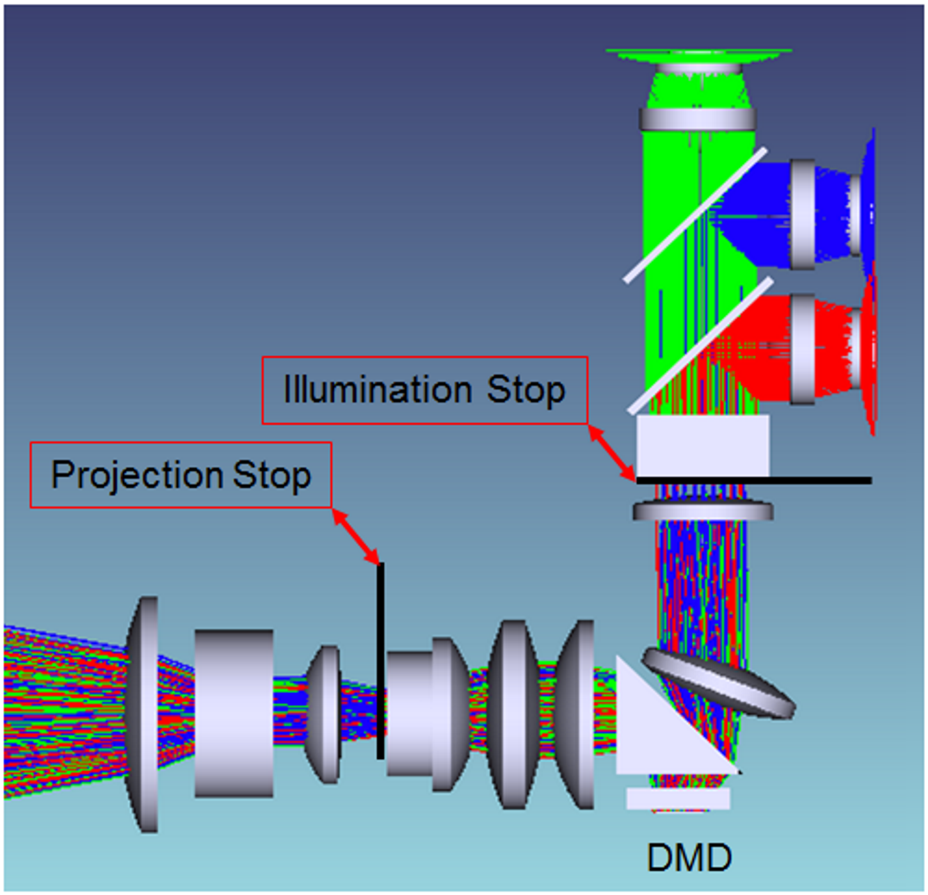

Figure 1. Typical Aperture Stop Placement

Using a DMD with a 5.4-µm TRP pixel having a 17 degree mirror tilt, TI has characterized the relationship between aperture stop size, brightness, and contrast. The figure below illustrates these relationships (It is important to note that these relationships will vary with each projector design).

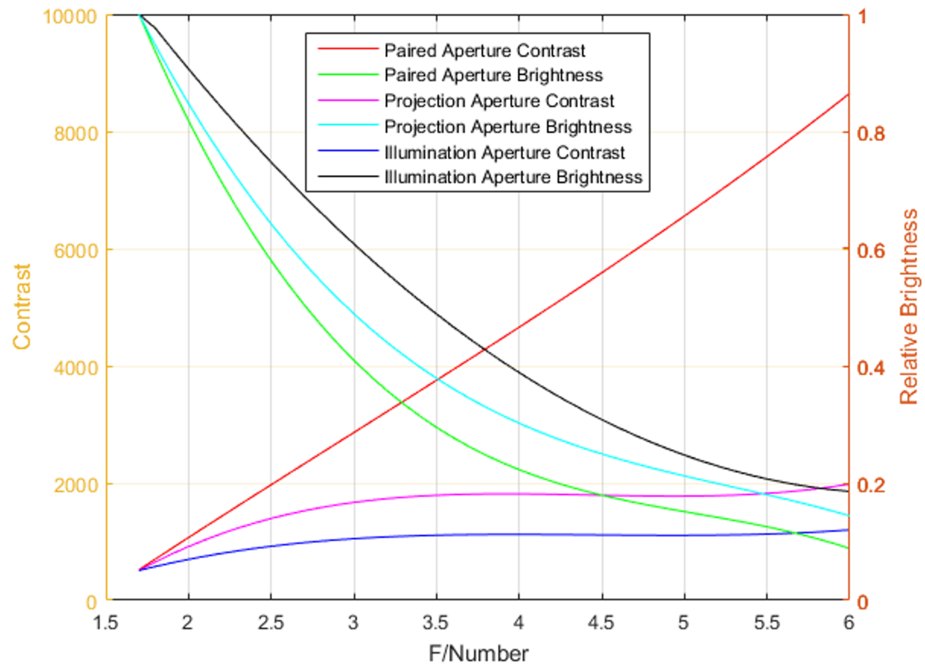

Figure 2. Relationship Between F/Number, Contrast, and Relative Brightness

When either the illumination stop or the projection stop is closed, the contrast increases in a logarithmic manner. Stopping down the illumination aperture from f/1.7 to f/6, while leaving the projection aperture at f/1.7, increased contrast by 236% with a brightness reduction of 81%. Similarly, stopping down the projection aperture from f/1.7 to f/6, while leaving the illumination aperture at f/1.7, increased contrast by 390% with a brightness reduction of 86%. When both aperture stops are closed simultaneously, contrast increases in a more advantageous linear manner. Closing down both apertures from f/1.7 to f/6 increased contrast by 1667% with a brightness reduction of 91%. Later in this paper, we'll discuss how to exploit these relationships to achieve the optimal balance between brightness and contrast for given ambient light conditions.

3 Projected Image System Contrast Ratio (PISCR)

Before the PISCR standard, contrast was specified using one of two methods, the Full on / Full off (FOFO) contrast ratio and ANSI contrast ratio. With both methods, measurements were taken in a completely dark room and directly from light emitted by the projector. The more commonly specified full on / full off contrast measurement is calculated by dividing the brightness measurement for a full black screen into the brightness measurement for a full white screen. Since most images are bimodal, containing both shadow and highlight detail, this contrast measurement does not adequately represent what an observer will encounter. The more optimal method, an ANSI standard that was retired in 2003, incorporates a sixteen zone black and white checkerboard pattern (see figure below). Contrast is calculated by taking the average brightness of all black squares and dividing that into the average brightness of all white squares. Not only is this test pattern a better representation of typical image data, it accounts for light scatter within the projection optics. Light scatter is where a bright object in the projected image, e.g., a white square, inflates the brightness of dark objects, e.g., a black square, due to scattering and internal reflection from inside the projection lens. The main flaws of both of these contrast measuring methods are that neither takes into account the projection screen or the amount of ambient light in the room.

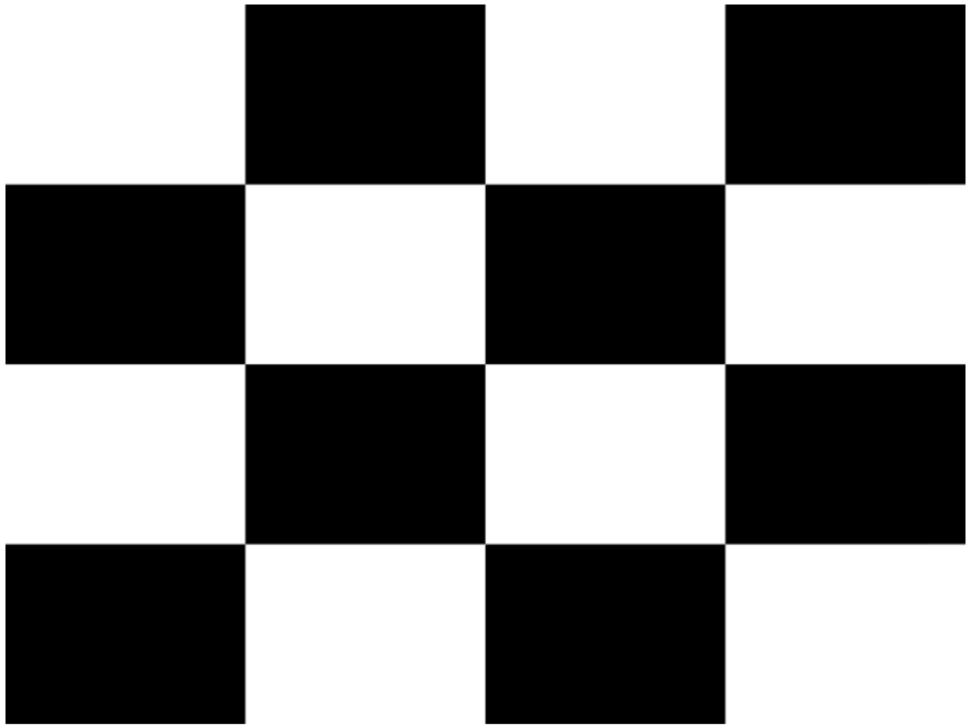

Figure 3. Sixteen Zone Checkerboard Pattern

The PISCR standard addresses screen and ambient conditions. Instead of measured illuminance, i.e. direct light from the projector incident on the screen surface, this standard uses measured luminance reflected from or transmitted through the projection screen so that the amount of ambient corruption is accounted for. As with the previous ANSI standard, a sixteen zone black and white checkerboard pattern is projected, the luminance of each black and white square is measured, and finally the PISCR is calculated as the average white luminance divided by the average black luminance. This system contrast measurement is a more representative objective metric for the image quality of a projector that an observer will perceive in a given viewing environment. As PISCR increases, image viewability, readability, and color vibrancy improve. The standard specifies minimum PISCR levels based on different use cases.

The following example illustrates how PISCR is a more meaningful contrast metric. Two projectors are being considered for a conference room that has a minimum, dimmed light level with an ambient light contribution at the projection screen of 100 lux. Using a 16-zone black and white checkerboard pattern, in a completely dark room projector 1 produces an average white square brightness of 500 lux and an average black square brightness of 0.25 lux for an ANSI contrast ratio of 2000:1. Projector 2, in a completely dark room, produces an average white square brightness of 750 lux and an average black square brightness of 1.5 lux for an ANSI contrast ratio of 500:1. At first glance, projector 1 might seem like the optimal projector since it has a large contrast advantage (400% improvement) for a relatively small brightness penalty (33% reduction). Taking the viewing conditions into account changes that perspective. Ambient light will contribute equally to the black and white measurements, so the PISCR of projector 1 will be (500 lx + 100 lx)/(0.25 lx + 100 lx) = 5.99, and the PISCR of projector 2 will be (750 lx + 100 lx)/(1.5 lx + 100 lx) = 8.37. Under these viewing conditions, the ambient light level dominates over each projector's black level. Hence, projector 2, with its brighter image, will produce a more vibrant, readable image.

The PISCR illustrates the importance of being aware of the viewing conditions. As ambient light contamination increases, projector brightness, not contrast, becomes the priority. With adjustable aperture stops, the optimal tradeoff between brightness and contrast, which maximizes the PISCR for a given ambient light level, may be obtained. The next section elaborates on how that optimization may be accomplished.

4 Automatic Adjustment of Aperture Stops

First, the system must be characterized at the appropriate brightness and contrast for given f-numbers. An optimal architecture would have dynamic control of both the illumination and projection apertures. If, however, due to cost or size constraints only a single aperture may be dynamically adjusted, an optimized architecture can still be achieved. This characterization only needs to be done once per design. For each distinct f-number, full on or full off contrast would be calculated by dividing the brightness for a full black screen by the brightness for a full white screen. Additionally, the relative brightness would be calculated by dividing the brightness for a full white screen for the given aperture position(s) by the brightness for a full white screen with wide open aperture(s). The number of discrete aperture positions could be as low as two, one for bright ambient conditions and the other for dark, or as many as the mechanical design will provide. The two position solution is an attractive architecture since it could provide great added value for little added cost. Potential mechanical architectures and stop selection for the two position solution are discussed further in the next section.

The following is an example characterization Lookup Table (LUT) for a 32 position TRP DMD system where both the illumination and projection apertures are controlled in an identical manner from f/1.7 to f/4.0. This LUT would be stored in the system, e.g., flash memory, to be referenced by the embedded software.

Table 1. Example Characterization LUT

F/Number	Contrast Ratio	Relative Brightness (Percent)
1.70	519	100.0000
1.77	656	95.2125
1.85	793	90.6192
1.92	929	86.2157
2.00	1064	81.9976
2.07	1199	77.9605
2.15	1333	74.1002
2.22	1467	70.4122
2.29	1601	66.8923
2.37	1734	63.5359
2.44	1867	60.3389
2.52	2000	57.2967
2.59	2132	54.4052
2.66	2265	51.6598
2.74	2397	49.0564
2.81	2529	46.5904
2.89	2661	44.2575
2.96	2793	42.0534
3.04	2925	39.9738
3.11	3057	38.0142
3.18	3189	36.1703
3.26	3321	34.4378
3.33	3454	32.8123
3.41	3586	31.2894
3.48	3719	29.8648
3.55	3852	28.5341
3.63	3986	27.2930
3.70	4119	26.1371
3.78	4254	25.0621
3.85	4388	24.0635
3.93	4523	23.1371
4.00	4659	22.2785

For optimal adaptation, two ambient light sensors should be used. One pointed at the projection screen, and one pointed away from the screen. The former serves two purposes, to measure the amount of ambient corruption at the projection screen and to measure the relative brightness of the projector itself. The latter shall be used to detect abrupt changes in ambient light, e.g. overhead lights being turned on. Detected changes in ambient conditions will, in turn, trigger a calibration event. For brevity, the sensor pointed towards the screen will be referred to hereafter as S_s, and the one pointed away from the screen will be referred to hereafter as S_a.

With regards to S_s, its placement and field of view (FOV) must be chosen to maximize the capture of projected light and minimize the sensing of light outside the screen bounds. This sensor will be used to determine the relative brightness of the projector in comparison to the ambient light in the room. Hence, if its FOV were wider than the projector, it would sense a larger ambient light contamination than what is actually occurring at the screen. The figure below illustrates a top down view of the geometry between the projection optics and this ambient light sensor.

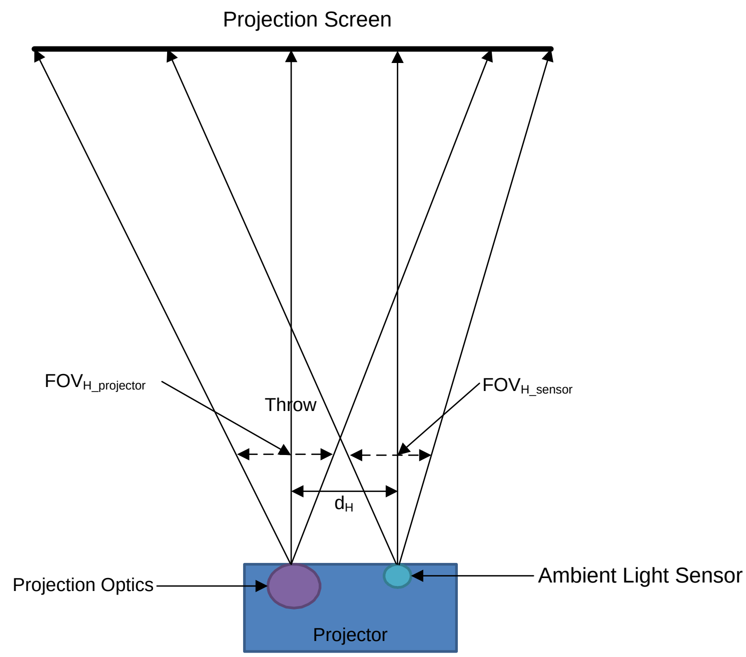

Figure 4. Top Down View of Projection Geometry

The relationship between throw ratio and horizontal FOV of the projection optics is as follows:

$FOV_{H\_projector} = 2*\tan^{-1}[(W/2)/T] = 2*\tan^{-1}[(W/T)/2] = 2 * \tan^{-1}[(1/(2*R)]$

where

- W = projected screen width
- T = throw distance
- R = throw ratio

With horizontal lens shift (HLS), the projected image may be moved to the right or left of the horizontal center line. HLS is specified as a percentage of the half width of the projected image. If HLS is adjusted to 100%, the left edge of the shifted, projected image would align with the horizontal center line. Similarly, if HLS is adjusted to -100%, the right edge of the shifted, projected image would align with the horizontal center line. HLS bounds must be taken into account when determining the most optimal horizontal FOV of the ambient light sensor.

Let d_H = horizontal distance between principal axis of projection optics and ambient light sensor

$FOV_{H\_sensor} = 2 * \tan^{-1}[(W/2 + (W/2)*HLS - d_H) / T] = 2 * \tan^{-1}[((W/2)(1 + HLS) - d_H)/T = 2 * \tan^{-1}[(1/(2*R))(1 + HLS) - d_H/T]$

The second term to the inverse tangent function will have its largest contribution when throw is minimized. Additionally, if a zoom projection lens is used, the maximum throw ratio will produce the most restrictive FOV. Also, the largest HLS, shifting the projected image away from the sensor, will constrain the FOV. Hence, the maximum throw ratio, minimum throw, and maximum HLS should be used in deriving the horizontal FOV of the ambient light sensor as follows:

$FOV_{H\_sensor} = 2 * \tan^{-1}[(1/(2*R_{max}))(1 – HLS_{opposite}) - d_H/T_{min}]$

where

- $HLS_{opposite}$ = Largest HLS amount shifting away from ambient light sensor

For further clarification, here is an example. An ambient light sensor is to be added to a projector with a zoom lens. The throw ratio range of this zoom lens is between 1.5:1 and 2:1. Additionally, the minimum expected throw is 100 inches, and HLS range is ±10%. The mechanical constraints force the ambient light sensor to be placed 4 inches to the right of the principal axis of the projection optics. The most restrictive horizontal FOV of the projector is 28.0725°, per the 2:1 throw ratio. Incorporating the 4 inch horizontal offset and 10% HLS, the ambient light sensor's horizontal FOV should be restricted to 20.9624° to prevent the measurement of light outside the bounds of the projected image.

The figure below illustrates a side view of the geometry between the projection optics and S_s.

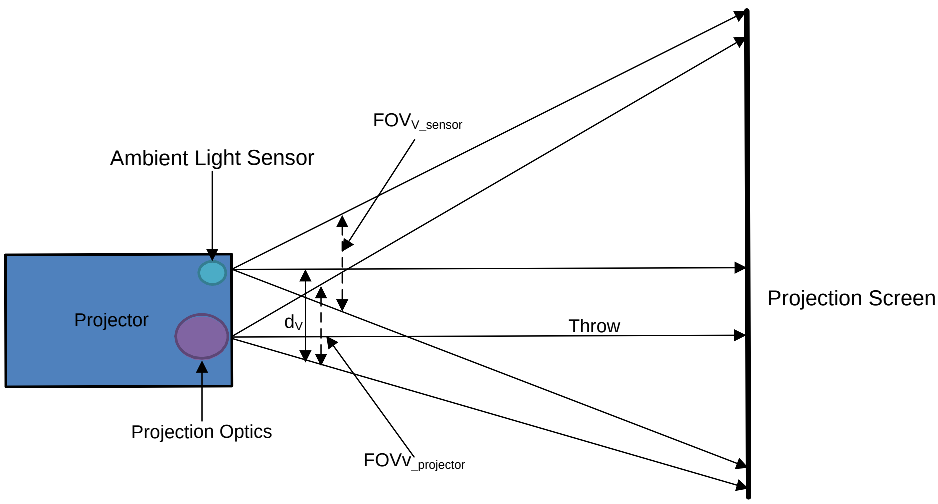

Figure 5. Side View of Projection Geometry

The relationship between throw ratio, aspect ratio, and vertical FOV of the projection optics is as follows:

$FOV_{V\_projector} = 2*\tan^{-1}[(H/2)/T] = 2*\tan^{-1}[((W/A)/2)/T] = 2 * \tan^{-1}[(W/T)(1/(2*A))] = 2 * \tan^{-1}[(1/(2*A*R))]$

where

- H = projected screen height
- A = aspect ratio of DMD = (width of DMD) / (height of DMD) = W/H

With vertical lens shift (VLS), the projected image may be moved above or below the vertical center line. VLS is specified as a percentage of the half height of the projected image. If VLS is adjusted to 100%, the bottom edge of the shifted, projected image would align with the vertical center line. Similarly, if VLS is adjusted to -100%, the top edge of the shifted, projected image would align with the vertical center line. Unlike HLS, the bounds of VLS are usually not symmetric around 0%. Typically the VLS bounds are centered around 100% to account for a projector being placed on a low table or hung on a high ceiling. A pitch should be applied to the ambient light sensor to account for this VLS offset.

$\theta_{top} = \tan^{-1}[(1/(2*A* R_{max}))(1 + VLS_{min}) - d_V/T_{min}]$

$\theta_{bottom} = \tan^{-1}[(1/(2*A* R_{max}))(VLS_{max} - 1) - d_V/T_{min}]$

$\theta_{sensor} = (\theta_{top} + \theta_{bottom})/2$

$FOV_{V\_sensor} = \theta_{top} - \theta_{bottom}$

where

- θ_{top} = pitch for top of projected image, with respect to the ambient light sensor
- θ_{bottom} = pitch for bottom of projected image, with respect to the ambient light sensor
- d_V = vertical distance between principal axis of projection optics and ambient light sensor (positive values for above principal axis)
- θ_{sensor} = optimum pitch of ambient light sensor

To continue with our example above, let's say our projector uses a 16:9 DMD, has a VLS range of 80% to 120%, and the ambient light sensor is to be placed 2 inches above the principal axis of the projection optics. The most restrictive vertical FOV of the projector, due to its 2:1 throw ratio, is 16.0095°. The pitch of the topmost edge of the projected image for the smallest VLS is 13.1227°, and the pitch of the bottommost edge of the projected image for the largest VLS is 0.4655°. Hence, the most optimal pitch and vertical FOV of the ambient light sensor is 6.7941° and 12.6572°, respectively. In summary, this sensor must only be allowed to see within the bounds of the projected image for all lens zoom positions and offsets.

Since HLS is centered on 0% and VLS is typically centered on 100%, the most optimal placement for S_s is directly above the projection optics. That placement will maximize the allowable FOV coverage. It may be desireable to mechanically relate the light sensor to the projection lens so that it will adjust its field of view simultaneously with any projection lens adjustments. The light sensor could be combined directly with the projection lens itself by using common optical elements or its own optics. A simple radiometer optical design (sensor placed at the back focal point of a lens) may work well in this application as the FOV could be controlled by a field stop and the sensor lens could be made very inexpensively since image quality is not required.

As stated previously, the second ambient light sensor, S_a, will be used to detect abrupt changes in an ambient environment. To prevent the projected image from falsely triggering such an event, the projection screen should not be within the FOV of this sensor. Continuing with the previous example, due to mechanical constraints, the second ambient light sensor is placed on the top side of our projector facing up, directly above the projection optics. From the equations above, we know that the pitch of the topmost edge of the projected image for the largest VLS is 17.1908° with respect to the principal axis of the projection optics. As long as the sensor's FOV for the dimension pointed towards the screen is less than 180° – 2 * 17.1908° = 145.6185°, the screen will not be visible by the sensor. It is desirable to have as wide a FOV as possible for this sensor, while still avoiding screen observability. This will minimize false triggers from pin point light sources like specular reflections. When the illuminance from this sensor increases or decreases by a large amount, e.g. 50%, a trigger for an abrupt ambient light change shall be issued. This ambient light sensor could be as simple as placing a diffuser element (a cosine diffuser type may be preferred) on top of, or some distance from, a photosensor. No lenses would be required since a large FOV of collection is needed. The sensor would best be shielded from directly seeing the ambient light scattering from the projection screen through mechanical baffles or mechanical positioning on the projector so that there is no direct path of light from the projected image to reach the sensor or sensor diffuser.

Whenever the projector is turned on or a trigger for an abrupt ambient light change has been issued, a calibration procedure is run. First, the aperture stop(s) are fully opened to provide for the largest signal to noise ratio (SNR) by S_s. Second, the projector is forced to display an all-black screen and S_s measures the corresponding brightness. Next, the projector is forced to display an all-white screen and S_s measures the corresponding brightness. From those two measurements, the ambient illuminance and projector illuminance may be derived as follows:

$MB_{lx} = W_{lx}/C_{f/1.7} + A_{lx}$

$MW_{lx} = W_{lx} + A_{lx}$

$A_{lx} = (C_{f/1.7} * MB_{lx} - MW_{lx})/(C_{f/1.7} - 1)$

$W_{lx} = MW_{lx} - A_{lx}$

where

- A_{lx} = ambient illuminance (lux)
- W_{lx} = white screen illuminance of projector (without any ambient light contribution)
- $C_{f/1.7}$ = FOFO contrast for wide open aperture stop(s), from characterization LUT
- MB_{lx} = illuminance measurement for an all-black screen with wide open apertures (f/1.7 in our example)
- MW_{lx} = illuminance measurement for an all-white screen with wide open apertures (f/1.7 in our example)

Once the projector's white screen illuminance is derived, the relative brightness values from the characterization LUT should be converted to illuminance values. Additionally, a system contrast value should be calculated for each entry using the following equations:

$WA[n] = WR[n] * W_{lx}$

$CS[n] = (WA[n] + A_{lx}) / (WA[n]/C[n] + A_{lx})$

where

- WR[n] = relative white screen brightness for aperture setting n (from characterization LUT)
- WA[n] = adjusted white screen brightness based on current W_{lx}
- C[n] = FOFO projector contrast for aperture setting n (from characterization LUT)
- CS[n] = system contrast for aperture setting n

Say for example, that S_s gives the following measurements: MB_{lx} = 20.2601 lux and MW_{lx} = 155 lux. Using the Cf/1.7 value from Figure 4, 519:1, ambient and white screen brightness can be derived: A_{lx} = 20 lx and W_{lx} = 135 lx. The system contrast values for our 32 aperture position example are given below.

Table 2. System Contrast for A_{lx} = 20 lx

F/Number	C[n]	WR[n]	WA[n]	CS[n]
1.70	519	100.0000	135.0000	7.6505
1.77	656	95.2125	128.5369	7.3548
1.85	793	90.6192	122.3359	7.0623
1.92	929	86.2157	116.3912	6.7771
2.00	1064	81.9976	110.6968	6.5010
2.07	1199	77.9605	105.2467	6.2350
2.15	1333	74.1002	100.0353	5.9793
2.22	1467	70.4122	95.0565	5.7342
2.29	1601	66.8923	90.3046	5.4997
2.37	1734	63.5359	85.7735	5.2756
2.44	1867	60.3389	81.4575	5.0618
2.52	2000	57.2967	77.3505	4.8581
2.59	2132	54.4052	73.4470	4.6643
2.66	2265	51.6598	69.7407	4.4801
2.74	2397	49.0564	66.2261	4.3054
2.81	2529	46.5904	62.8970	4.1397
2.89	2661	44.2575	59.7476	3.9829
2.96	2793	42.0534	56.7721	3.8347
3.04	2925	39.9738	53.9646	3.6948
3.11	3057	38.0142	51.3192	3.5630
3.18	3189	36.1703	48.8299	3.4389
3.26	3321	34.4378	46.4910	3.3222
3.33	3454	32.8123	44.2966	3.2128
3.41	3586	31.2894	42.2407	3.1102
3.48	3719	29.8648	40.3175	3.0142
3.55	3852	28.5341	38.5210	2.9246
3.63	3986	27.2930	36.8456	2.8410

Table 2. System Contrast for A_{lx} = 20 lx (continued)

3.70	4119	26.1371	35.2851	2.7631
3.78	4254	25.0621	33.8338	2.6906
3.85	4388	24.0635	32.4857	2.6233
3.93	4523	23.1371	31.2351	2.5609
4.00	4659	22.2785	30.0760	2.5030

For this amount of ambient light contamination, it is clear that system contrast is maximized by setting the apertures to f/1.7. Each time this calibration procedure is run, the maximum system contrast must be found by traversing through each entry in the characterization LUT.

Here is a second example for further clarification. The S_a sensor detects an abrupt change in ambient conditions which triggers the calibration procedure. The following measurements are taken from black and white screens: MBlx = 0.3101 lux and MWlx = 135.05 lux. This corresponds to an ambient and white screen brightness of 50 mlx and 135 lx, respectively. The adjusted white screen brightness and system contrast ratios are calculated for each entry in the characterization LUT as shown in the figure below.

Table 3. System Contrast for A_{lx} = 50 mlx

F/Number	C[n]	WR[n]	WA[n]	CS[n]
1.70	519	100.0000	135.0000	435.4828
1.77	656	95.2125	128.5369	522.8376
1.85	793	90.6192	122.3359	599.1387
1.92	929	86.2157	116.3912	664.2906
2.00	1064	81.9976	110.6968	718.9560
2.07	1199	77.9605	105.2467	764.2449
2.15	1333	74.1002	100.0353	800.3926
2.22	1467	70.4122	95.0565	828.4788
2.29	1601	66.8923	90.3046	849.1565
2.37	1734	63.5359	85.7735	862.8451
2.44	1867	60.3389	81.4575	870.5263
2.52	2000	57.2967	77.3505	872.8538
2.59	2132	54.4052	73.4470	870.3040
2.66	2265	51.6598	69.7407	863.8471
2.74	2397	49.0564	66.2261	853.7575
2.81	2529	46.5904	62.8970	840.7476
2.89	2661	44.2575	59.7476	825.3290
2.96	2793	42.0534	56.7721	807.9748
3.04	2925	39.9738	53.9646	789.1171
3.11	3057	38.0142	51.3192	769.1443
3.18	3189	36.1703	48.8299	748.4064
3.26	3321	34.4378	46.4910	727.2138
3.33	3454	32.8123	44.2966	705.8782
3.41	3586	31.2894	42.2407	684.5443
3.48	3719	29.8648	40.3175	663.4920
3.55	3852	28.5341	38.5210	642.8477
3.63	3986	27.2930	36.8456	622.7755
3.70	4119	26.1371	35.2851	603.3335
3.78	4254	25.0621	33.8338	584.6736
3.85	4388	24.0635	32.4857	566.7918
3.93	4523	23.1371	31.2351	549.7694
4.00	4659	22.2785	30.0760	533.6238

From the figure above, it is clear that an aperture setting of f/2.52 will maximize system contrast (to 873:1) for this level of ambient light corruption.

From these two examples, one can see how powerful ambient aware aperture optimization may be. We have significantly different optimal aperture settings for the two different scenarios. If we were forced to use a fixed f/2.52 aperture, the optimal aperture for the second case, the first case would have a 36% reduction in system contrast. Likewise, if we were forced to use a fixed f/1.7 aperture, the second case would have a 50% reduction in system contrast.

5 Cost Minimization

Two options are available to the system designer to minimize cost: reduction of the number of aperture stops and elimination of the screen ambient light sensor, S_s. The tradeoffs will be discussed here.

The number of aperture stops may be reduced down to as far as two values. Even though this particular architecture cannot be optimized for a continuum of ambient light levels, it is an attractive solution for two reasons. First, a simple, low cost mechanical solution may be implemented to achieve the two aperture stops, and second, the apertures may be chosen for two extreme cases, lights on with high ambient contamination and lights completely off with no contamination.

One way to achieve such a simple two stop solution is to rotate in a more restrictive aperture as shown in the figure below.

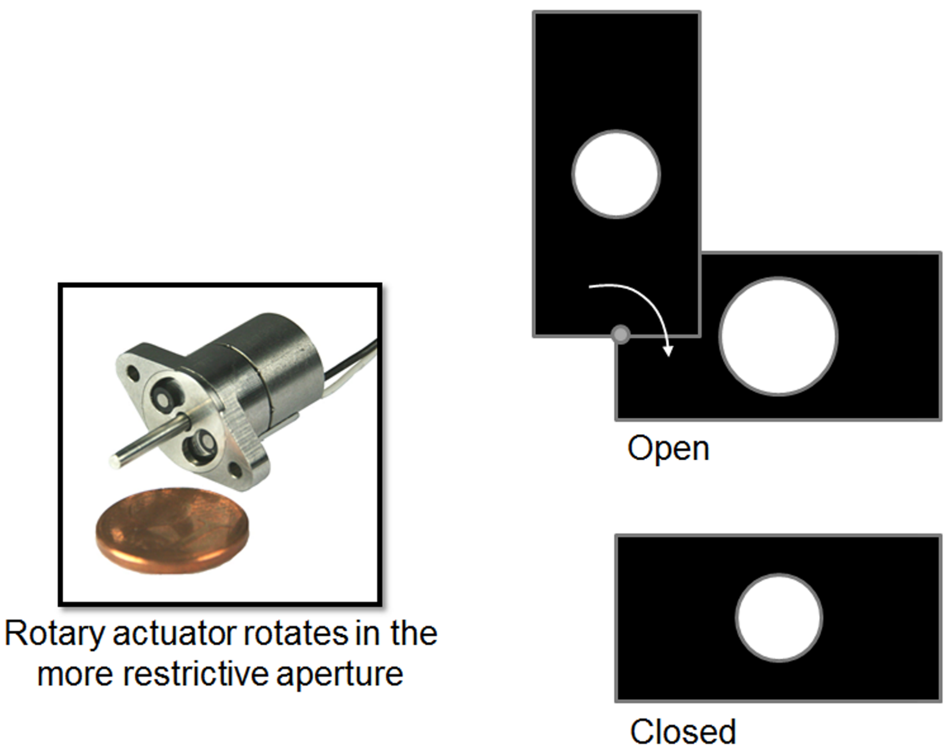

Figure 6. Two Stop Mechanism Using a Rotary Actuator

The determination of the wide open aperture f-number will be dictated by optical constraints, i.e. how fast can the optics run for a reasonable cost. The selection of the more restrictive aperture f-number may be made based on the brightness requirement for the largest supported screen size. For example, we have characterized the contrast and brightness of a potential projector design for 32 possible aperture stops, as shown in the table below.

Table 4. Potential Aperture Stops for a Two Position System

F/Number	Contrast	Brightness (Lumens)
1.70	519	3000.0000
1.77	656	2856.3750
1.85	793	2718.5760
1.92	929	2586.4710
2.00	1064	2459.9280
2.07	1199	2338.8150
2.15	1333	2223.0060
2.22	1467	2112.3660
2.29	1601	2006.7690
2.37	1734	1906.0770
2.44	1867	1810.1670
2.52	2000	1718.9010
2.59	2132	1632.1560
2.66	2265	1549.7940
2.74	2397	1471.6920
2.81	2529	1397.7120
2.89	2661	1327.7250
2.96	2793	1261.6020
3.04	2925	1199.2140
3.11	3057	1140.4260
3.18	3189	1085.1090
3.26	3321	1033.1340
3.33	3454	984.3690
3.41	3586	938.6820
3.48	3719	895.9440
3.55	3852	856.0230
3.63	3986	818.7900
3.70	4119	784.1130
3.78	4254	751.8630
3.85	4388	721.9050
3.93	4523	694.1130
4.00	4659	668.3550

The projector in this example has a 16:9 aspect ratio, and the system designer wants to support screen sizes up to a 150 inch diagonal. Using the DCI brightness requirement of 14 fL, the brightness of the projector should be at least 935 lumens. For quick reference, the relationship between footlamberts (fL) and lumens is given here: fL = (lumens)(screen gain)/(area of screen in ft^2). Looking over the characterization data given in the figure above, it is clear that an f/3.41 aperture would satisfy that brightness requirement. Hence, the most optimal aperture stops for this projector would be f/1.7 and f/3.41. The calibration procedure, as described above, will still be implemented, but only two system contrast ratios need be calculated. When ambient light levels are high, f/1.7 will be selected, providing the brightness needed to minimize light contamination, and when ambient light levels are low, f/3.41 will be selected, providing an attractive 3,586:1 contrast ratio.

For further cost reduction, S_s may be eliminated. With this elimination, the designer loses the ability to measure the relative brightness of the projector with respect to the ambient light level, but certain assumptions may be made to estimate that relationship. In particular, the designer may assume that the ambient brightness measured by S_a will be close to the ambient brightness derived by S_s measurements. In other words, assume that ambient brightness is the same on-screen as it is elsewhere in the room. Additionally, the designer may use the largest supported screen size in deriving the relationship between ambient and projector brightness. Since this will result in the largest ambient light contribution, it is a conservative estimate. This is best explained with an example. The projector in this example has a brightness of 3000 lumens, at f/1.7, and a 4:3 aspect ratio. The system designer wants to support screen sizes up to a 120 inch diagonal. This projector will use a 16 stop aperture design, and the characterization LUT for this projector is as shown in the table below.

Table 5. Example Characterization LUT for Single Sensor System

F/Number	Contrast Ratio	Relative Brightness (Percent)
1.70	519	100.00
1.79	679	94.43
1.87	838	89.12
1.96	997	84.07
2.05	1155	79.26
2.13	1312	74.70
2.22	1468	70.38
2.31	1624	66.29
2.39	1780	62.42
2.48	1935	58.76
2.57	2090	55.31
2.65	2245	52.06
2.74	2399	49.01
2.83	2553	46.15
2.91	2708	43.46
3.00	2862	40.95

Since no brightness measurement will be taken directly from the screen, the illuminance of the projector, WA[n], will be estimated based on the largest supported screen size. The equation relating screen size, lumens, and illuminance is as follows: illuminance = (lumens)/(area of screen in ft^2). For this example, the ambient brightness measured by S_s is 100 mlx. The estimated projector illuminance and system contrast is given in the LUT below.

Table 6. System Contrast for Single Sensor System, A_{lx} = 100 mlx

F/Number	C[n]	WR[n]	WA[n]	CS[n]
1.70	519	100.00	62.5000	283.9983
1.79	679	94.43	59.0188	316.2998
1.87	838	89.12	55.7000	335.2639
1.96	997	84.07	52.5438	344.7367
2.05	1155	79.26	49.5375	347.3565
2.13	1312	74.70	46.6875	345.0650
2.22	1468	70.38	43.9875	339.2492
2.31	1624	66.29	41.4313	330.9116
2.39	1780	62.42	39.0125	320.8122
2.48	1935	58.76	36.7250	309.5152
2.57	2090	55.31	34.5688	297.4855
2.65	2245	52.06	32.5375	285.0555
2.74	2399	49.01	30.6313	272.5179
2.83	2553	46.15	28.8438	260.0605
2.91	2708	43.46	27.1625	247.7689
3.00	2862	40.95	25.5938	235.8446

For this example, the estimate for the most optimal stop setting is f/2.05, with a system contrast estimate of 347:1. To give a sense of the estimation error, let's assume that the actual screen size is only 80 inches. Our estimate for projector illuminance would be off by a factor of 2.25, and the most optimal stop setting would be f/2.31 with a system contrast of 593:1. With f/2.05, the system contrast of our 80 inch screen is only reduced by 4% to 568:1, so at least for this example, our assumptions have provided a near-optimal result.

Since the cost of ambient light sensors are relatively low (<$1), elimination of S_s is not recommended unless the projector will have a fixed throw. Two fixed throw examples are: An ultra-short throw projector on a fixed mounting arm and a heads up display (HUD). With a fixed throw system, the size of the screen is known and hence projector illuminance, WA[n], will be constant, ignoring temperature, lifetime, and manufacturing variability.

6 Special Case: Automotive Head-Up Display (HUD)

The ambient light levels for automotive HUDs are defined by the external scene illumination and albedo of the driving environment. The displayed virtual image is seen as being directly overlaid or floating on top this environment. In this case, there is no diffusing surface for which the ambient light and the projected light to scatter from. The background scene itself is the scattering object and the background light emitted by this scene from external illumination (sunlight for example) directly contributes to the background level on which the virtual image is viewed. These ambient light levels have a significant impact on the readability and minimum contrast levels for a virtual display. The ambient conditions depend on the degree of sunlight, the ever-changing reflectivity of the landscape, and the changes in artificial lighting of the road at night. A dynamic aperture system for projection based picture generation units (PGUs) for automotive HUD using DLP technology would be ideal for this demanding display environment, providing the brightness for daytime high ambient light conditions while achieving high contrast and low brightness for night conditions without being uncomfortably bright to the viewer.

During the day the HUD image must be bright and can have inherently low contrast due to the bright ambient background. The most important factor for daytime conditions is display brightness vs the ambient landscape brightness. According to Gish [1] the displayed virtual image content should be at about a level of half the maximum brightness of the scene. The ambient scene brightness levels may far exceed the maximum brightness levels of the HUD image. In this case, the dark areas of the HUD image cannot be seen at even low contrast levels. However, under modest driving ambient light conditions, the background contrast may be seen (letterbox effect) if the HUD brightness is set too high. HUDs require that the brightness be adjusted based on the brightness of the ambient environment for optimal viewing to minimize distraction of the HUD image overlay. Currently, dynamic dimming algorithms use the built in dashboard light sensor to detect the ambient lighting conditions and automatically adjust the light sources to lower the HUD brightness level and maintain display readability with little or no letterbox effect.

Night conditions are more demanding on contrast levels of the HUD display than daytime conditions. The background of night conditions can vary significantly due to street lighting conditions and the HUD brightness can be easily be set higher than would be optimal. Under these conditions, the PGU must achieve a high level of contrast to prevent the grey letterbox condition described above. Luminous flux (lumen) level requirements at night are much less those required during daytime driving. The addition of a dynamic aperture to the DLP PGU can significantly increase the contrast of the HUD during night driving conditions at the expense of virtual image brightness, which is not required at night or dim ambient conditions. Relative aperture control of the PGU optimizes the contrast and brightness for the large dynamic range of viewing conditions.

DLP electronic dimming algorithms can currently achieve 5000:1 on-state dimming levels. For example, 15000 nits of brightness for daytime use down to 3 nits for use at night in the lowest ambient lighting conditions. Without the use of a dynamic aperture, the contrast of the display will remain constant throughout the dimming range. The control of the f-number of the PGU through swappable or dynamically adjusting apertures offers the ability to optimize the brightness and contrast performance of HUD displays to more effectively match ambient conditions and can potentially provide a dimming control beyond 5000:1 with DLP technology. Methods of incorporating a dynamic aperture in a HUD PGU system may be as sophisticated as incorporating a dynamic adjustable iris, which offers the most flexibility to control contrast and brightness, or as simple as a two position aperture as shown in Figure 7. Other methods include a sliding or rotating aperture with two or more stop positions of the PGU optics, or a method for slowly rotating an aperture for a more dynamic approach that could be used as an alternative to an iris diaphragm. The optimal level of contrast improvement from a given relative aperture (f/#) of a PGU system requires that the apertures in both the illumination and projection optics be adjusted and matched to provide the same f-number for both the illumination and projection optics.

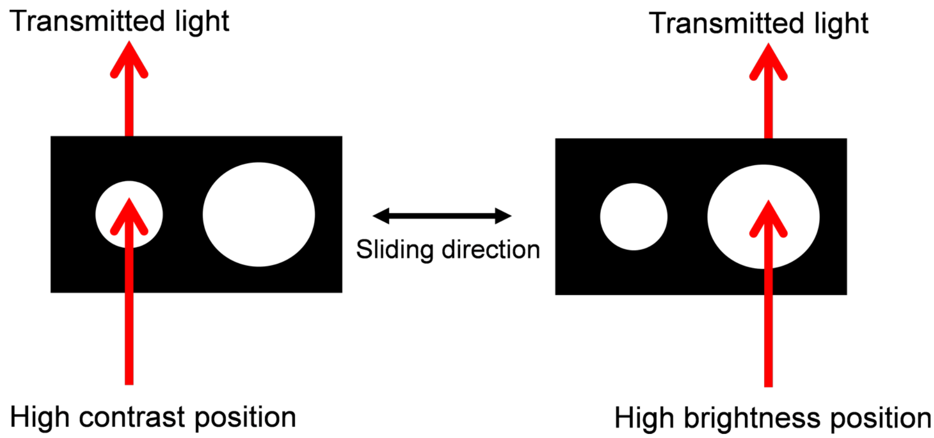

Figure 7. Two Position Sliding Aperture Option for High Contrast and High Brightness Operating Mode

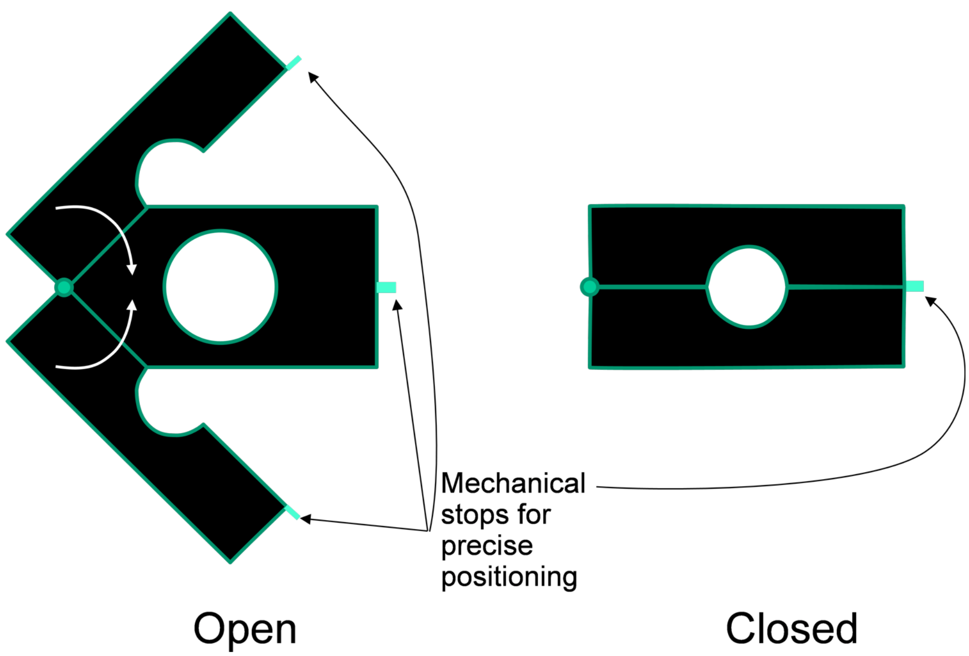

Figure 8. Alternative Two-stop Position Mechanism Using a Rotary Actuator

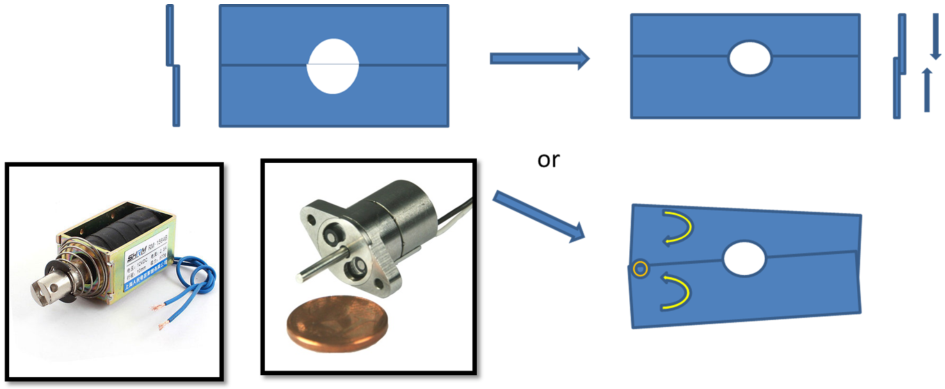

Figure 9. Alternative Guillotine Type Continuous Closing Aperture Using a Rotary or Linear Actuator

The dynamic aperture in the PGU can be included in the calibration so that the color balance and HUD brightness decrease can be smoothly transitioned over the complete range of required brightness levels. A higher f-number for night conditions provides contrast levels for improved and less distracting HUD displays. Optimization of the DLP PGU f/# allows the viewable virtual display to have an optimized level of contrast and brightness for the demanding and ever-changing ambient brightness of the automotive environment.

7 References

- [1] Gish, K.W. & Staplin, “Human Factors Aspects of Using Head Up Displays in Automobiles” USDOT, Washington 1995
- [2] Martin, Thompson, Ferri, “Augmented Reality Head-Up display: Defining Brightness Requirements”, IDW

8 Trademarks

DLP is a registered trademark of others.