Enhanced optical design by distortion control

Simon Thibault[a], Jonny Gauvin[b], Michel Doucet[b], Min Wang[b]
Optical Department
[a]ImmerVision, 2020, University, Montreal, Quebec, H3A 2A5, Canada
[b] INO, 2740 Einstein Street, Sainte-Foy (Qc), G1P 4S4, Canada

ABSTRACT

The control of optical distortion is useful for the design of a variety of optical system. The most popular is the F-theta lens used in laser scanning system to produce a constant scan velocity across the image plane. Many authors have designed during the last 20 years distortion control corrector. Today, many challenging digital imaging system can use distortion the enhanced their imaging capability. A well know example is a reversed telephoto type, if the barrel distortion is increased instead of being corrected; the result is a so-called Fish-eye lens. However, if we control the barrel distortion instead of only increasing it, the resulting system can have enhanced imaging capability. This paper will present some lens design and real system examples that clearly demonstrate how the distortion control can improve the system performances such as resolution. We present innovative optical system which increases the resolution in the field of view of interest to meet the needs of specific applications. One critical issue when we designed using distortion is the optimization management. Like most challenging lens design, the automatic optimization is less reliable. Proper management keeps the lens design within the correct range, which is critical for optimal performance (size, cost, manufacturability). Many lens design presented tailor a custom merit function and approach.

Key words: Optimization, distortion, lens design, wide angle lens.

INTRODUCTION

In is simplest expression, the distortion is a transverse deformation of an image. If a grid is used as an object, its image in a system with distortion will be a grid of curved lines. This is due to the change in the transverse magnification in a system as a function of the distance from the optical axis. When the magnification decreases as the distance from the axis increases, a barrel shaped image occurs. If the magnification increases with the distance, a pincushion image is obtained. Visually most people do not notice distortions of less than a few percent however for precision digital imaging applications optical distortion will result in a significant resolution penalties. But managing distortion can be very interesting! Ten year ago I read a paper: Doing more with less from David Shafer[1], he essentially said that achieving ever higher performance levels in optical design does not always require going to more cost and/or complexity in the designs. Often it is possible to make major performance improvements by questioning assumptions that have crept in at the very beginning of the design process. Using such design philosophy can produce new type of optical design, and in particular using distortion.

It is well known that many optical systems have distortions. One of the most popular is certainly the F-theta lens used in laser scanning systems to produce a constant scan velocity across the image plane (we call it F-Theta distortion). Another example is a reversed telephoto. Starting with a reversed telephoto and its legendary barrel distortion type, and instead of trying to remove it, you have increased it to such an extent that the image height is actually proportional to the field angle itself rather than to its tangent, you will have a lens called a fish-eye lens (called fish-eye lens because it resembles that image of the whole sky reduced to a finite circle as would be seen by a fish looking upwards through the surface of water). When designing a fish-eye you still have a departure from the ideal linear function between the field angle and the pixel coverage. This produces a reduction in the resolution (pixel per degrees) of the scene you looking. Current number for the distortion can be as large as 15 to 20% which corresponds to a penalty of more than 150 to 200 pixels for a 1 Meg Pixel sensor. This is a very huge number of pixels which cannot be used for detection, recognition and identification.

Optical Design and Engineering II, edited by Laurent Mazuray, Rolf Wartmann
Proc. of SPIE Vol. 5962, 596211, (2005) · 0277-786X/05/$15 · doi: 10.1117/12.625151

Today, many challenging digital imaging systems can enhance their imaging capability by managing the distortion. The distortion now becomes a new degree of freedom for optical designers. Since much of the persons working with optical software have a little or no background in optics, using distortion as a design variable is not an easy task. Those persons attack new problems not from a fundamental understanding but based on their past experience. However using imagination and theoretical background, a qualified specialist can design a new variety of optical systems that can enhance the use of digital imaging systems. By controlling the distortion, we can manage the relation between the field of view and the pixels for a given application[2].

2. CASE STUDY: WIDE ANGLE LENS

For video surveillance of offices, stores, indoor parking, houses, the camera is usually mounted on the ceiling, its lens facing down as shown in figure 1. The most significant and often distant objects are in the zone at the periphery of the lens. This part of the picture is the most significant because it allows faces recognition. Current system of video surveillance will required IP camera with 2 Mpx and more in order to get a recognition range of 2.4 m around the camera (half sphere surface). This assumption is based on 20 pixels X 20 pixels within the face of the subject to be recognized. A rough indication of the practical meaning of resolution requires 8 resolution line pairs per the height of the target (Johnson's law)[3]. New IP camera infrastructure is quite complex, time consuming and costly for old security installation. Many security system already operational uses standard NTSC camera linked to standard TV monitor or computer with digital or analog recorder. For those installations, the upgrade for IP system is a real issue. In order to reduce the pressure on the camera architecture, we can redesign the lenses to use efficiently each pixel as well as the overall camera sensor (CCD or CMOS).

To maximize the optical performance, the lens is designed to increase the picture resolution in the particular area, the areas of interest. By controlling the slope of the distortion profile, we can impose a section with higher resolution and some section of the FOV with a lower resolution... If we compare this new kind of optical component performance with the fish-eye lens, an improvement factor up to 3.5 in resolution can be achieved (figure 1-2).

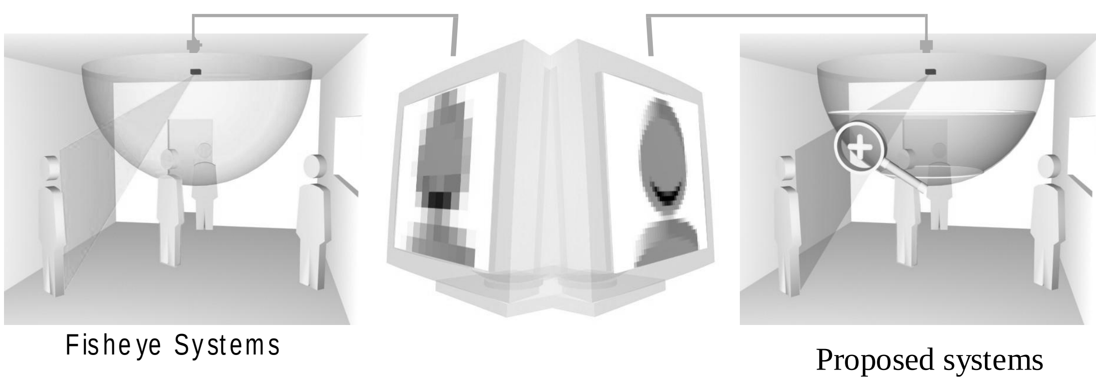


Figure 1: Indoor Video Surveillance (periphery increased resolution)

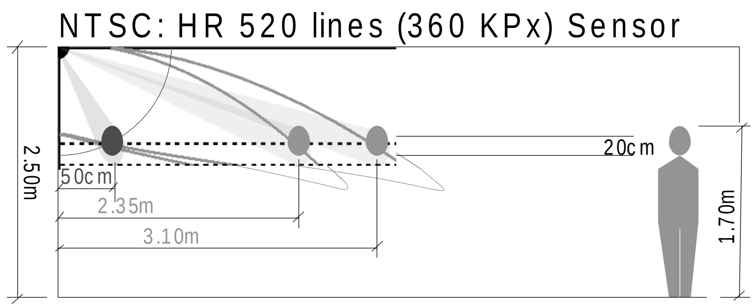


Figure 2: Distance to recognize a face (20 pixels wide).

Using the optics to get such new image distribution profile, we can raise the distance where we can recognize a face. With the past 9/11 event, many public location will need a better imaging capability. Because the cost is always an issue, lenses with new capabilities will certainly help. By using distortion control approach, already installed low resolution camera can be used which can reduce the cost of the overall system. The other advantageous of using a new lens type was the bandwidth. Many security and surveillance system must use wireless transmission. By using a new lens with better pixel coverage on a low resolution camera (0.3Mpx) we will get the same quality level as a 2 Mpx with a standard fisheye. The figure 2 shows that with a fisheye lens, you can recognize a human face at 50 cm and at more than 2 m with a controlled distortion profile. The 2.35m and the 3.10 m range is the value that you can obtain if you implement also an anamorphic magnification in order to cover the overall 4:3 sensor as shown in the figure 3.

(a) (b)

Figure 3(a): Fish-eye lens generates circular image; (b) Anamorphic lens produces elliptical image.

Figure 4 shows a graphical representation of the distortion profile uses for the resolution calculation. Each circle corresponds to the chief ray positions of the detector plane. The left hand side represents an ideal linear distribution (f-theta) like a fisheye lens. The right side shows some field compression from 0 to 306 degrees and a field expansion between 54 and 72 degrees.

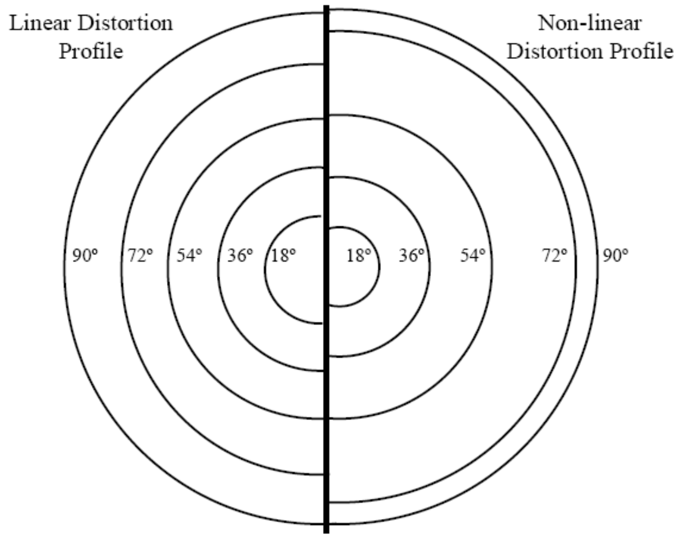


Figure 4: Fields positions on the detectors for two distortion profile.

If we compared the pixel per angle as a resolution increase, we will find the curve shown in the figure 5 (in the figure the angle start from top to bottom).

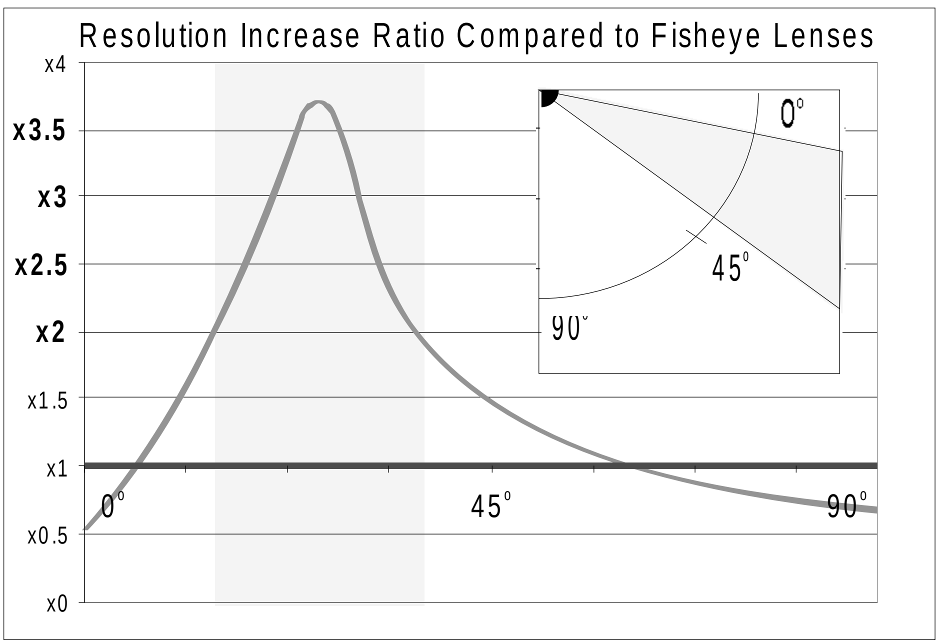


Figure 5: Resolution increase ratio calculation.

This case study shows that the distortion control can help to the pixel coverage, not by creating pixels but simply by a new distribution of the image on the sensor. Defining the zone of interest should be the first step. The challenge is now for the optical designer…

There are other interesting applications which can benefit from distortion control. To make video-conferencing as efficient as a normal face to face meeting, the same single camera can be placed on the table, its lens now facing up (figure 6). The distortion profile of the lens will help to increase the resolution where the heads of the people are normally positioned.

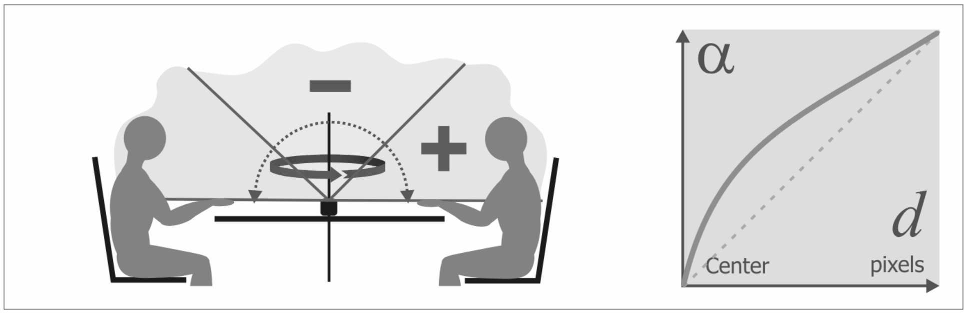


Figure 6: Video-conferencing (periphery increased resolution).

In contrast, some wide-angle lens applications may require that the resolution should be higher in the area in front of the lens such as ATM surveillance applications. For ATM surveillance, it is important to know what happens around the ATM to improve the efficiency of the security but most important information is in front of the camera (to recognize the person). So a wide-angle lens with center increased resolution is perfectly suitable for the purpose. We can also imagine that such lens could be used in a mobile phone, this will allow an individual to use his mobile phone to participate in a video-conference. The wide-angle feature allows him to be always in the field of view of the camera even if he does not handle its phone correctly.

For most outdoor surveillance scenarios like a 360 degrees video surveillance system, fish-eye lenses are widely used. However, if we use a horizon increased resolution distortion profile, up to 3X resolution increase than a fish-eye can be expected in the green zone as shown in figure 7. The goal is always to increase the resolution in the field of interest. This also helps to reduce the pressure on the software part by providing efficient imaging system.

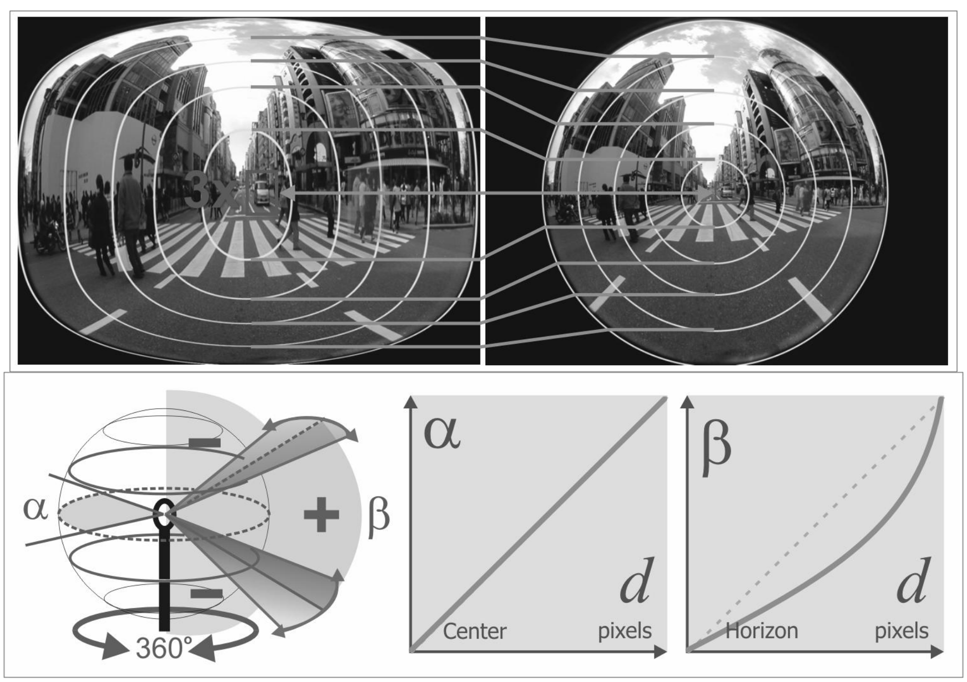


Figure 7: Outdoor 360^o surveillance system (horizon increased resolution).

Although the choice of the distortion profile is often complex, there are factors that you must always take into account: the applications, the minimum acceptable resolution, and the cost. These factors are certainly not independent, other factors like wavelength range, light level and environment will influence one or more of the three factors. To choose the proper distortion profile for your application, you should consider every information and calculate to benefit from it.

3. THE DISTORTION: CONTROL/CORRECTION

Theoretically, the Seidel Third-order contribution to distortion varies as the cube of the object height or which means that the fractional distortion can be expressed as the square of the object height. The Seidel coefficients show that the distortion (not only) depends on the chief ray trace. Because the chief ray trace is determined by the location of the aperture stop in the optical system, relocation of the aperture strop position will change the aberrations of the optical system. In fact, the effect of stop shift on the aberration indicates that the distortion can be corrected or controlled by a complex (more or less) equation. The equation of the new distortion after stop shift is a non-linear combination of the original aberration (without stop shift), distortion, astigmatism, field curvature, coma and spherical aberration of the system. Over the years, since 1900, it was fund that using a symmetrical system about the stop eliminates the distortion. A lens system strictly symmetrical about the aperture stop will be a 1:1 relay lens which is not really applicable for many wide angle digital imaging applications. However a lens design starting point with a symmetric power distribution around the aperture strop (+ - + or - + -) could be more promising that unsymmetrical forms (- +, + + -).

Today we will try to control the distortion. As discussed earlier, the distortion can be controlled or corrected by controlling the aperture stop position (entrance pupil) as well as other aberrations. As example in a wide angle lens, the entrance pupil moves as shown in the figure 4. From a certain point of view, this entrance pupil shift is equivalent to a stop shift. This stop shift can be used to control the distortion. Of course the calculation of the distortion control by the aberration stop shift equation is not easy and some what inefficient, but the concept is there. Since the front lens group is responsible from the larger amount of distortion, it can be used for the distortion controlled and the impact of the rear group can be negligible on the final distortion profile. As far as we know, the distortion control is best achieved by constrains perhaps with larger weighting at later design stages when you have most of your lens design in hand.

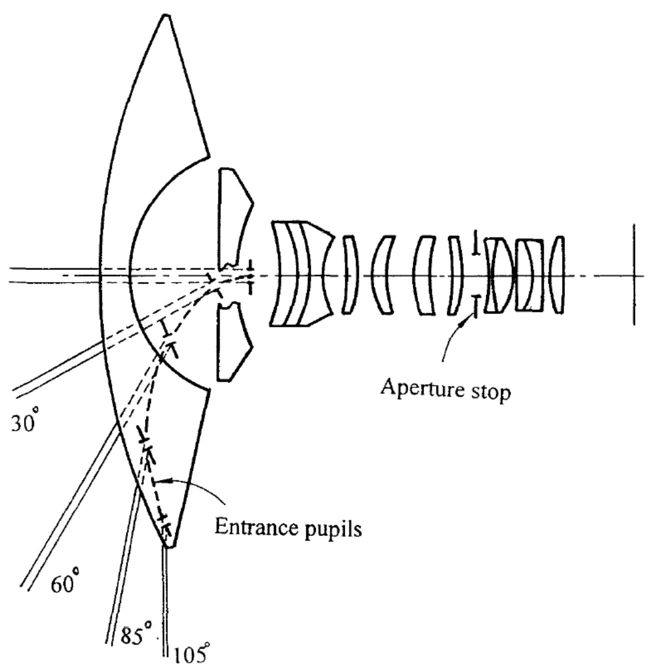


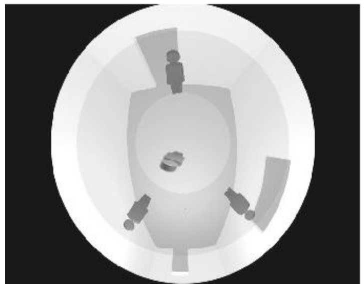
Figure 8: Lakin's very wide angle lens with the positions of the different entrance pupils[4].

For those who are interested by more details about the distortion optimization, you can find a discussion in the following paper wrote by the same author, Development of New Family of Wide-Angle Anamorphic Lens with Controlled Distortion Profile[5].

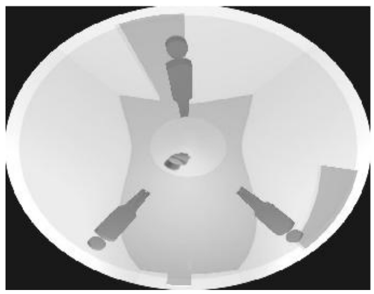
4. LENS PROTOTYPE

At ImmerVision, we have designed and built a new type of anamorphic distortion controlled lens. The figure 9 shows a typical image taken on a standard camera. The gain with the distortion profile is schematically presented in the figure 10. The gain in the zone of interest is presently evaluated at 3 times the resolution of a standard fisheye lens. The new lens is called: Panomorph lens.

Figure 9: Image taken with ImmerVision Panomorph lens.



Fisheye:
Sensor surface used: 50.9%
Pixels used in interest area: 29.1%



Panomorph Lens:
Sensor surface used: 78.5%
Pixels used in interest area: 50.3%

Figure 10: Schematic comparison with a fisheye lens and the Panomorph lens.

5. CONCLUTION

In conclusion, managing distortion is an innovative approach in many optical fields, particularly for digital imagery. By using better pixel coverage, a system with a low resolution can be enhanced to high resolution in some zone of interest. This can be used to update some existing system or to get new applications. The design of such system is not an easy task but the ImmerVision prototype's shows that such system is clearly feasibly.

REFERENCES

1. David Shafer, Doing more with less, Proceeding of SPIE Vol 2537, August 1995.
2. Simon Thibault, Distortion Control Offers Optical System Design a New Degree of Freedom, Photonics Spectra, May 2005, pp. 80-82.
3. Modern Optical Engineering, 3rd edition, Warren J. Smith, McGraw-Hill, p. 376.
4. Fallah H.R. and Maxwell J., Higher Order Pupil Aberrations in Wide Angle and Panoramic Optical Systems, Proceeding of SPIE Vol. 2774 (August 1996).
5. Gauvin, J., M. Doucet, M. Wang, S. Thibault, and Blanc, B., Development of New Family of Wide-Angle Anamorphic Lens with Controlled Distortion Profile, Proceeding of SPIE 5874 (-4), August 2005.