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Developments in modern panoramic lenses: lens design, controlled distortion and characterization

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ABSTRACT

Almost every aspect concerning the design of modern panoramic lenses brings new challenges to optical designers. Examples of these include ray tracing programs having problems finding the entrance pupil which is moving through the field of view, production particularities due to the shape of the front lenses, ways of tolerancing these systems having strong distortion, particular setups required for their characterization and calibration, and algorithms to properly analyze and make use of the obtained images. To better understand these modern panoramic lenses, the Optical Engineering Research Laboratory at Laval University has been doing research on them during the past few years. The most significant results are being presented in this paper.

Controlled distortion, as in commercial panomorph lenses (Immervision), is used to image a specific part of the object with more pixels than in a normal fisheye lens. This idea is even more useful when a zone of interest vary in time with dynamically adjustable distortion as in a panoramic locally magnifying imager. Another axis of research is the use of modern computational techniques such as wavefront coding in wide-angle imaging systems. The particularities of such techniques when the field of view is large or with anamorphic imagers are considered. Presentation of a novel circular test bench in our laboratories, required to calibrate and check the image quality of wide-angle imaging system, follows. Another presented setup uses a laser and diffractive optical elements to compactly calibrate wide-angle lenses. Then, a discussion of the uniqueness in tolerancing these lenses, especially the front elements due to the large ratio between lens diameter and entrance pupil diameter, is included. Lastly, particularities with polarization imaging and experiments of triangle orientation detection tests before and after unwrapping the distorted images are briefly discussed.

Keywords: Optical design, wide-angle lens, panoramic, panomorph, distortion,

1. INTRODUCTION

Wide-angle lenses are generally considered to be lenses having a field of view greater than 60 degrees. Fisheye lenses are characterized by an even larger field of view which covers a hemispherical field. Panoramic lenses are used for optical systems having a field of view 130 degrees or more. Fisheye and panoramic lenses have an inherent large distortion, but the distortion should not be considered as an aberration but rather the result of the projection of a hemispheric field (3D) on a 2D sensor. Distortion, by itself, does not degrade image quality; it only changes the image height in respect to the field angle. However, when the distorted image is sampled by an imaging array like a CCD, the object space angle subtended by a given pixel varies with its position within the field of view. This produces a variation in the resolution (pixel per degrees) of the observed scene. If one controls the barrel distortion, the resulting system can have enhanced imaging capability. By controlling the distortion, one can design the relation between the field of view and the pixels for a given application[1, 2], and thus the resolution of the system can be increased at given regions of interest in the field of view. Distortion now becomes a new degree of freedom for optical designers.

Panoramic lenses having a controlled distortion are called panomorph lenses. These lenses are also categorized as anamorphic imagers, relating to the fact that the distortion profile is not rotationally symmetrical, as shown on figure 1. Another advantage of panomorph lenses is that the image footprint is a super-ellipse and thus covers more efficiently the rectangular sensor area.

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Figure 1: Comparison between images from a panomorph lens (left) and from a regular fisheye lens (right)

The increased resolution (in pixel/degree) of a panomorph lens in comparison with a fisheye lens of the same focal length is shown as a ratio in figure 2b. In the designed region of interest, the augmented resolution can be as high as over 3.5 times the resolution of a conventional fisheye.

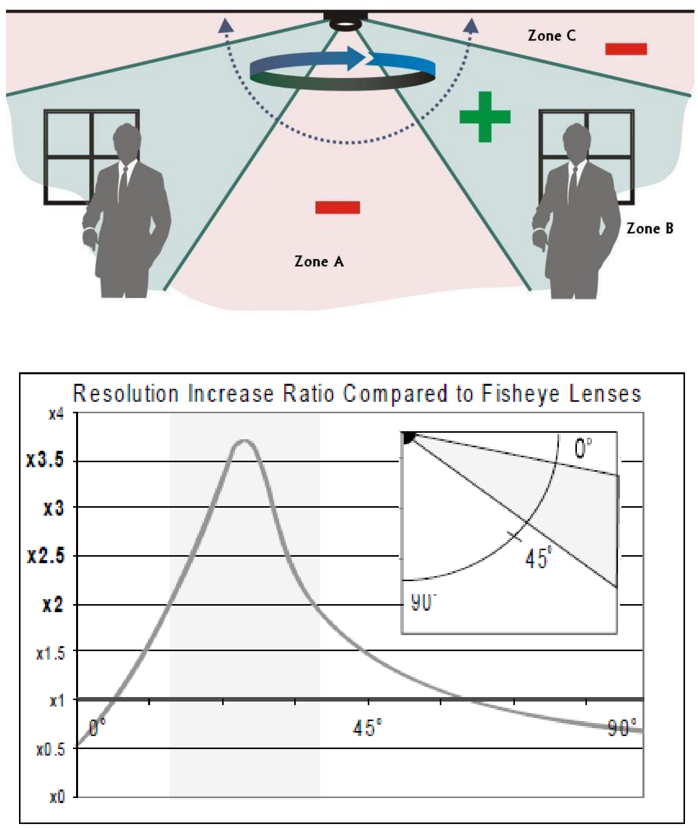

Figure 2: (top) Surveillance scenario with a panomorph lens showing higher resolution zones, (bottom) Comparison of the number of pixels per angle as a resolution increase between a panomorph lens and a fisheye lens, Figure taken from Thibault et al.[3].

Designing these types of panoramic lenses is not a simple task as many supplemental considerations must be taken into account. The first part of this paper will present the numerous challenges associated with the design and tolerancing of wide angle optics and how to overcome them. Section 3 presents how we can further push the capabilities and performances of panoramic lenses by dynamically adjusting the distortion profile for time-varying regions of interests and by using wavefront coding. The final section will cover the testing and characterization of the fabricated panomorph lenses and briefly show how they perform in polarization imaging and in target acquisition with the triangle orientation method.

2. LENS DESIGN AND ANALYSIS

Beside their large FOV, the main advantage of panomorph lenses is that resolution can be increased for particular field angles by controlling the non-linear distortion profile of the lens. The resolution profile, and thus the distortion profile, can be specifically tailored to a given application. The best way to produce and control such distortion is to add an aspheric shape at the front surface of the first lens. The main purpose of this lens is to control the direction of chief ray according to the required distortion profile.

2.1 Design considerations

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[4]. Seidel coefficient show that distortion depends mainly on the chief ray trace and can thus be controlled or corrected by shifting the aperture stop position. From a certain point of view, this entrance pupil shift is equivalent to a stop shift. For example, figure 3 shows the entrance pupil shifts for two types of wide angle lenses. In a typical wide-angle lens the entrance pupil moves away from the optical axis as field angle increases[5]. However, the displacement of the entrance pupil position for a panomorph lens is more complicated, as it is shown on figure 3. These pupil shifts make it more difficult for optical design programs to trace rays in the system and thus their positions must be determined for each field position. The entrance pupil positions are determined by launching rays that are angularly very close to each other, from the aperture stop, towards the object space. The intercept (or the distance of closest approach) of these two rays after all refractions is then the image of this point of the stop through the object space, which is by definition the entrance pupil. This procedure must be repeated for all analyzed field angles.

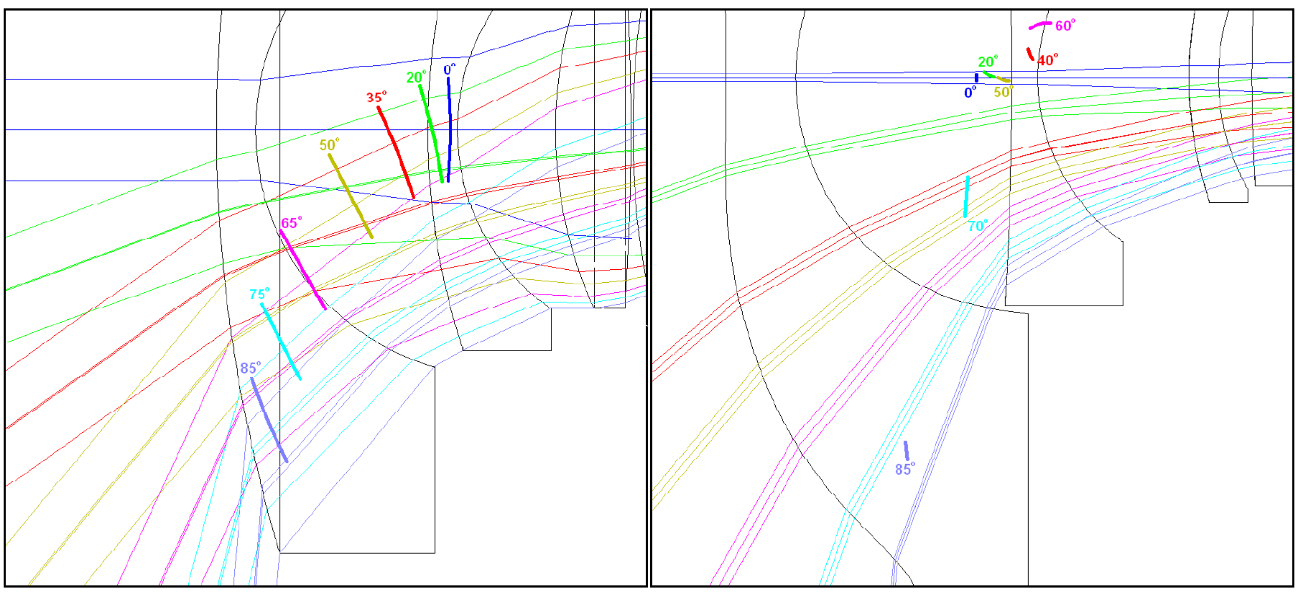

Figure 3: Entrance pupil displacement at various fields of views for a standard wide-angle fisheye lens (left) and the Panomorph lens (right). Figure taken from Parent et al.[8]

In order to maximize the rectangular sensor coverage of the produced image, the lens effective focal lengths along the orthogonal axis must have a ratio equivalent to the sensor ratio (4:3). To create this anamorphosis, cylindrical lenses are added to the back end of the panomorph lens design.

2.2 Tolerancing panoramic lenses

Tolerancing is a rather straightforward procedure in lens design. A set of mechanical and manufacturing tolerances is defined, compensators with their allowable ranges are added and finally quality criterion (MTF, RMS spot size, wavefront errors etc.) are selected for a given application. However, for wide angle imaging systems, tolerance analysis can be more challenging and proper tolerances have to be specified to ensure that the required performances are achieved. These are often very sensitive[6] and ray tracing errors are frequent in optical design programs at large field angles due to large entrance pupil shifts. Any changes in the localized curvature of the front surface give rise to important change in the total distortion of the system. Not all the distortion is produced by the first surface of the system but it has the most impact on it compared to the contributions from the other surfaces. A possible explanation of this is that the front surface produces the greatest angular variations of the rays and thus the final angle for a given height on then detector is greatly dictated by this surface. The impact of localised errors on the front surface, errors in the front surface slopes, and entrance pupil displacement for panoramic lenses has been extensively analyzed in Parent et al.[7, 8].

3. ADVANCED IMAGING METHODS APPLICATION

We here present methods in advanced imaging used to further increase the capabilities of panoramic lenses.

3.1 Active distortion control imaging

Panoramic lenses discussed until this section had zones of augmented resolution that were designed for a specific application. These regions are mainly produced by the shape of the frontal lens and are static. By using an active optical element such as a deformable mirror or a spatial light modulator, it is possible to actively control in real-time the distortion and consequently the local resolution of a given region of interest while maintaining a constant field of view. The resolution can be increased within a zone of interest, at the expense of decreasing it somewhere else in the remaining field of view.

A prototype of a system with dynamical distortion control has been constructed and tested using a deformable mirror [9]. The active element used is a 91-actuator magnetic liquid deformable mirror as this application requires deformation of large amplitude. The technical details of this ferrofluidic mirror are given in Brousseau et al.[10].

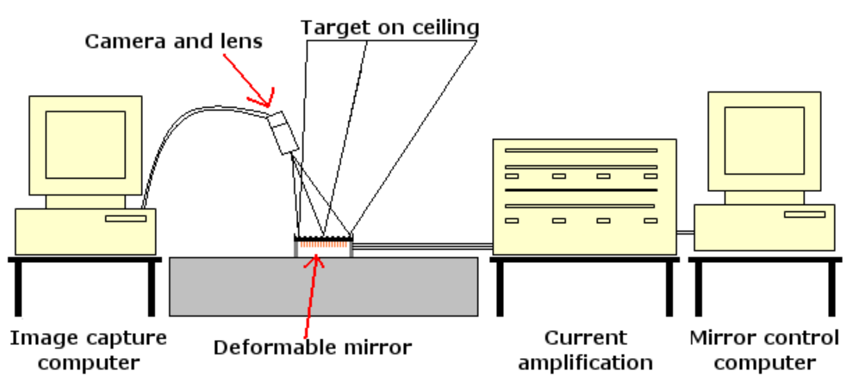

Figure 4: Diagram of the active distortion control experimental setup. Figure taken from Parent[11]

An experimental result from this system is presented in figure 5. Local magnification power increase effect can be clearly seen at the picture on the right. A loss in resolution is observable for a small area surrounding the augmented resolution zone.

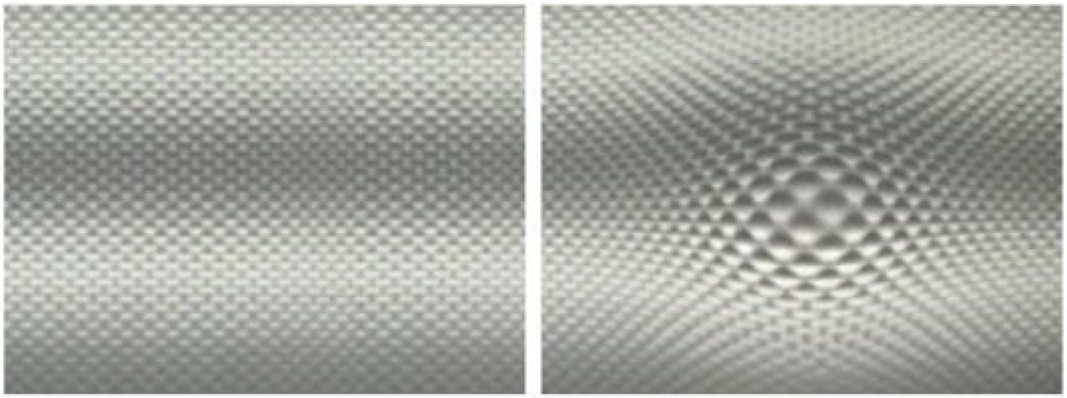

Figure 5: Experimental results of the active distortion control system before (left) and after applying a deformation on the liquid mirror (right)

3.2 Wavefront coding

Wavefront coding is a technique developed to enhance the depth of focus of imaging systems[12] but it can also be used to reduce focus-related aberrations[13-15] and ease tolerancing [16,17]. Wavefront coding is performed by placing a phase mask near the aperture stop of the system. The phase mask degrades the point spread function (PSF) of the system but this degradation renders the PSF invariant for different depths of field (DOF). The extended DOF image is restored by performing a deconvolution of the resulting image with the predicted PSF. Research on this method has been applied almost exclusively on optical systems with narrow FOV for which the PSF remains the same over the FOV. Unlike traditional wavefront coding systems, which only require the constancy of the modulation transfer function (MTF) over an extended focus range, wavefront-coded panoramic systems particularly emphasize the mitigation of significant off-axis aberrations such as field curvature, coma, and astigmatism

Distributed wavefront coding is a method where a second optical surface is designed to further encode the system. Since the front element of a panomorph lens contributes greatly to its distortion profile, it cannot be used for distributed wavefront coding. Likewise, surfaces near the stop cannot affect field position-wise aberrations independently. Therefore, only the very few last surfaces of the system can be modified. These surfaces can affect the field independently and reduce aberrations, like coma, that affects the performance of the system using a phase mask. The last surface of the panomorph design is hence changed from a spherical to an extended aspheric surface. Figure 6 shows the simulated results of deconvoluted images for different fields. Sharpness at high spatial frequency is improved for both wavefront coded systems which indicates reduced impact from astigmatism and field curvature. The distributed wavefront encoded system simulated images show less artefact than the wavefront coded one. This can be attributed to the fact that the PSF of the distributed wavefront coded system is more constant over the entire FOV of the system.

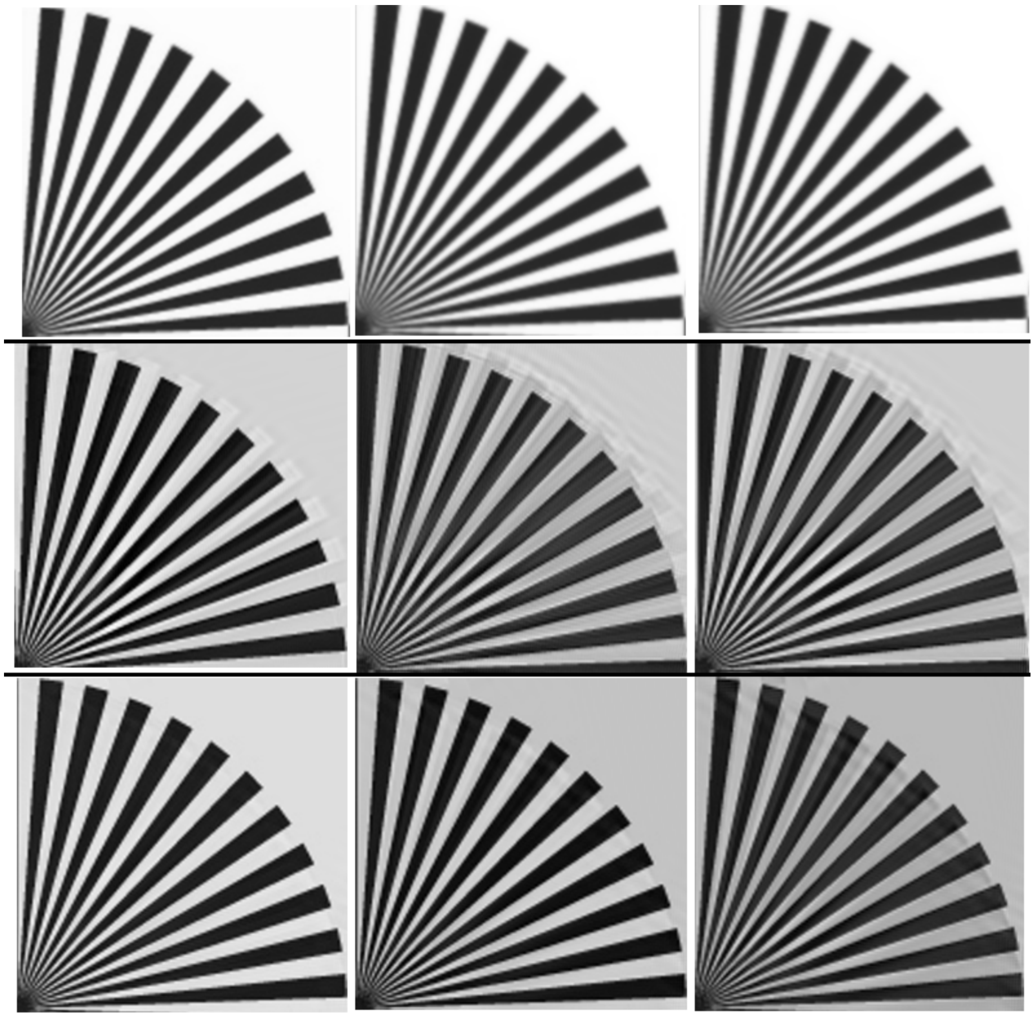

Figure 6: Image simulation for the three systems: the first row show simulation for the original system at three different fields, the second row show the simulation for the wavefront coded system (phase mask only) and the third for the distributed wavefront coding (phase mask plus aspheric last surface) all for the same field and wavelength. Figure taken from Larivière-Bastien et al.[18]

3.3 Specific polarization imaging behaviour

In defense and security applications, the polarization of light can convey additional information in order to discriminate manmade objects against different natural backgrounds and it is thus a valuable asset for target acquisition and contrast enhancement of manmade objects. Since panoramic lenses have a very large FOV, the field angles in respect to the different optical surfaces can have a great range of values. This affects the imaging properties at different field positions for polarization-sensitive targets. This effect must be considered in security applications but it can also be taken advantage of. An extensive research of the polarization imaging properties of panoramic lenses will be presented in Désaulniers et al. [19].

4. TESTING AND CHARACTERIZATION

4.1 Characterization setup

Characterization of panoramic lenses is a delicate task due to their varying field-dependant properties. A setup has been created to measure the inverse of the instant field of view $(IFOV)^{-1}$ for different panoramic lenses and also the MTF of several panoramic systems [20]. It is a cylindrical structure of 75 cm interior radii covering a field of view of 220°. The camera-lens system is placed at the center of curvature of the cylinder. Various sets of targets can be placed on the setup to perform different measurements. Pictures of the setup are shown at figure 7.

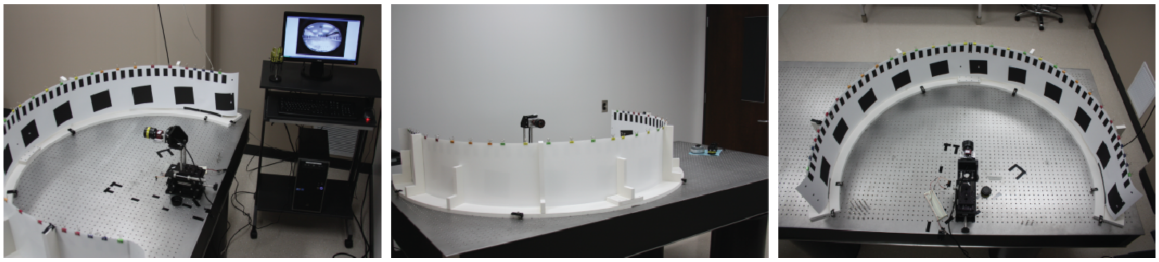

Figure 7: Setup for panoramic lenses' measurement of $(IFOV)^{-1}$ and image quality (MTF). Figure taken from Poulin-Girard[21].

Several lenses have been characterized with this setup. To measure $(IFOV)^{-1}$, a series of black and white stripes of 2° angular-width each is used. Each stripe is considered as an object and its position in the object plane is referenced. We determine the position of each stripe on the sensor of the camera (image plane) and get the relation between the angle of the stripes in the field of view in the object plane and the position of the stripes on the sensor. This relation between the object and the image plane can be derived to obtain $(IFOV)^{-1}$ in pixels/degrees for the entire field of view. Experimental results were compared with Zemax simulations and showed good concordance.

To perform image quality measurements, slanted-edges are used to determine the MTF for different angles within the field of view. The target used is a series of black and white 10° of angular-width squares tilted at an angle of 5.71°. For each slanted-edge, corresponding to a specific angle in the field of view, the line spread function (LSF) is obtained and the MTF is calculated by performing the Fourier transform of the LSF [22]. For each MTF, only the spatial frequency where the modulation is 50% (f50) is kept and associated with the angle of the corresponding slanted-edge in the object plane. Image quality profiles are the relation between the angle of the field of view in the object plane and frequency f50. Higher is the frequency, better is the image quality. Profiles have been obtained for several camera-lens systems. Asymmetries in the profiles showed that this type of measurement is sensitive to errors of manufacturing.

4.2 Triangle orientation discrimination

The triangle orientation method (TOD) is an emerging technique for the evaluation of electro-optical (EO) systems mainly used in the field of defence and security [23, 24]. This method has been developed to circumvent the problem of applying classical methods, such as the minimal resolvable temperature difference (MRTD) for thermal imagers and the minimum resolvable contrast (MRC) for visible spectrum imagers, on modern sampling array like CCDs. In this method, the test pattern is a non-periodic equilateral triangle in one of four different orientations (apex up, down, left, or right), and the measurement procedure is a robust four-alternative forced-choice psychophysical process. The characterisation metric of this method, just as the MRTD and MRC methods, is target acquisition distance.

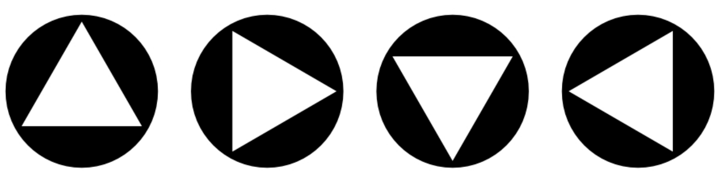

Figure 8: Typical shape of TOD test targets

The study of using this method on highly distorted OE systems, like hemispheric imagers, has been presented in Désaulniers et al.[25]. TOD method was applied to both unprocessed and unwrapped images. In order to reduce the measuring time that comes with applying this method to wide FOV systems, an automated process, which includes a test-target registration process and an orientation discriminator process, was developed.

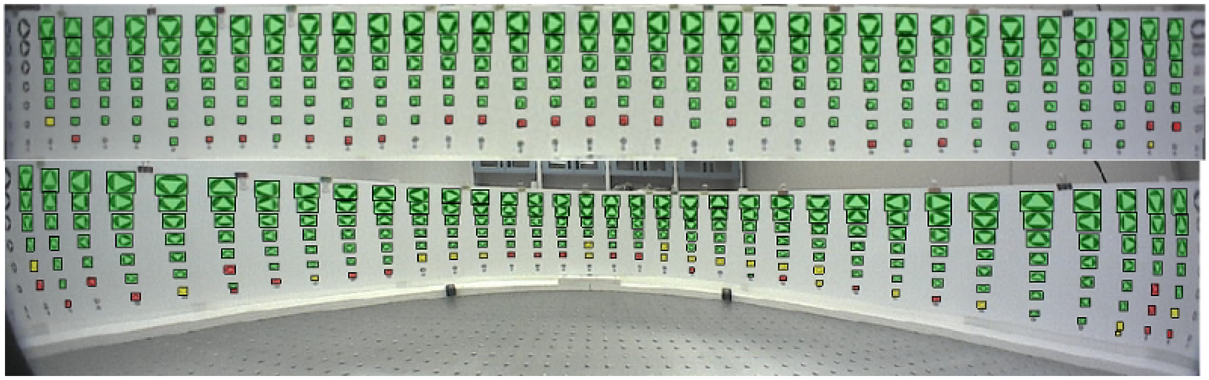

Figure 9: Typical orientation discrimination results of processed (top) and unprocessed (bottom) wall-type image. Correct orientation discrimination is represented by a green square, a yellow square indicate a correct orientation discrimination but having a low correlation value and low confidence factor, a red square indicates a failed orientation discrimination. (Colors are shown on the electronic version of this paper). Figure taken from Désaulniers et al.[25].

4.3 Measuring distortion using diffractive optical elements

A method for geometrical calibration of a camera using diffractive optical elements (DOE), first developed by Bauer et Al.[26], has been applied to panoramic imagers in order to measure precisely their distortion profile. As the virtual sources, the diffracted points are at infinity which gives precise calibration targets under a compact package in comparison to more classical calibration methods that usually use precisely surveyed target in the field [27]. The adapted method uses crossed dot-line generating diffractive elements in order to get the largest fan out angle as possible in order to maximize the field coverage by the diffracted points.

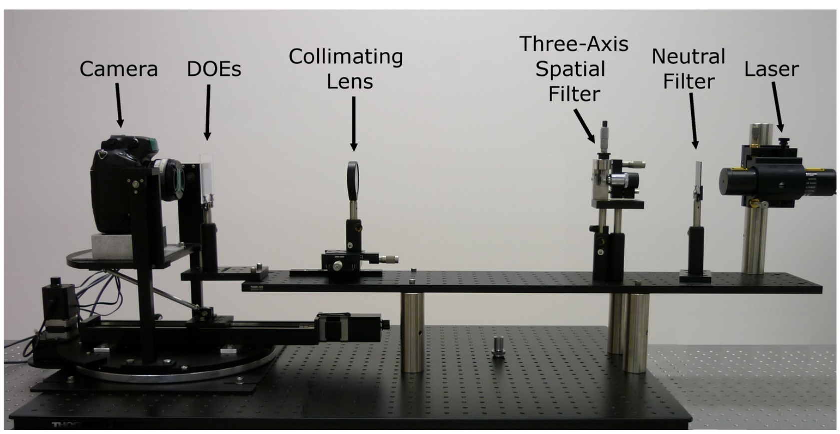

Figure 10: Picture of the calibration setup with the crossed gratings. Figure taken from Thibault et al.[27].

The positions of the diffracted points on the CCD are given by a centroid detection algorithm able to provide sub-pixel accuracy. The distortion profile's parameters and other intrinsic camera parameters are then calculated via a non-linear optimisation algorithm which uses the positions of the diffracted points as well as a modified mathematical representation of the diffracted beam that takes into account the clocking errors of the DOE. Results of this calibration method applied to panoramic imagers will be presented in a future article.

5. CONCLUSION

Modern panoramic lenses offer added capabilities such as augmented resolution in specific region of interest while having a very large field of view. These added features are obtained by controlling the distortion of these lenses.

However, designing such lenses comes with lots of challenges ranging from ray tracing errors to their specific tolerancing. Distortion control can be achieved in real-time by using an active optical element such as a deformable mirror or a spatial light modulator. This dynamical distortion profile can produce zones of increased resolution while maintaining a constant FOV. Wavefront coding for wide angle systems, where the imaging properties change within the FOV, was also studied by our group. The distributed wavefront coding approach is a novel concept that utilizes a second surface to compensate aberrations that affects the performance of the system using a phase mask. Simulation results show that distributed wavefront coding can be effectively applied to panoramic imagers. Finally, with varying imaging properties over the FOV, the testing of such lenses must be adapted from conventional methods when characterizing panoramic lenses.

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