Wide-angle lens miniaturization through foveated imaging

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ABSTRACT

In the recent years, there have been many improvements in optics miniaturization, including wide-angle lenses. However, the design of a miniature wide-angle lens (FFOV 180°) is not a simple task. In order to correct aberrations that are issue from the large field of view, many lenses are necessary. Moreover, the amount of distortion is usually very high for those kinds of designs.

It has been reported that distortion can be used as a design parameter in order to control the local magnification of the image across the field of view. This control of the distortion can be used to enhance the quality of the information present at the center of the image at the expense of the sides, leading to a foveated design. By carefully adjusting the resolution across the field of view, less care can be given to correcting defects issue from the edge of the field. This sort of compromise is a promising way to release some constraints and could, for example, allow a reduction of the number of lenses in the system.

The present paper explores the effect of the control of distortion toward foveated imaging on a wide-angle lens. The goal is to assess its potential for allowing the simplification of the system. In order to achieve this objective, a miniature wide-angle lens is modified into different foveated designs, each of them with different resolution targets. The starting design is a state of the art commercial miniature wide-angle. The conditions in which the system can be reduced are then analyzed. Finally, the results and findings are discussed.

Keywords: Lens design, imaging system, foveated imaging, miniaturization

1. INTRODUCTION

Miniaturization of optical system has been an important issue in the last decades [1-2]. Constant improvements in optics manufacturing have led to the integration of miniature cameras in a wide variety of system [3]. Key aspects behind those improvements were the development of new plastics, the reduction of the thickness of plastic lenses and an increase in manufacturing precision leading to narrower tolerances. To a certain extent, these aspects will continue to play an important role as they push the physical limits behind new designs. However, they do not hold all the answer. In order to address certain issue arising from complex designs, it is essential to consider alternative approaches that allow for a reduction in size of the optical system. In the case of wide-angle lens, foveated imaging is a valid option.

Foveated imaging is inspired from the human eye. It is an optical system with a large field of view where the center region is able to capture a much higher resolution than at the limit of the field of view. The reason for this is mainly a higher concentration of cones in the center region called the fovea. In order to compensate for the lack of resolution on the sides, the eyes is able to center any region of interest on the fovea by moving. The first systems using foveated imaging reproduced this kind of geometry by adjusting the spatial response of a custom-designed sensor [4]. Later, it was shown that a similar effect could be produced by grouping pixels outside the center region in order to reduce to total amount of information going through the system. Using this technique, it was even possible to choose a region of interest outside the center of the field of view. Even though these techniques are directly inspired from the morphology of the human eye, foveated imaging can be achieved through other means.

Much attention has been devoted in the last years to the use of a spatial light modulator (SLM) in order to achieve foveated imaging [5-7]. The ability of the SLM to correct the wavefront deformation for a specific set of chosen angles is more versatile than many other solutions. By using a tunable phase element, not only can we chose to enhance the center region of the field of view, but we can also improve other region if needs be. However, the usual size of such a device, whether it is working in transmission or reflection, can be a problem for miniature application.

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A more direct way to generate a foveated imager is to split our low resolution and high resolution information in two different channels [8-10]. In that kind of design, one set of lenses is responsible for the wide-angle fields and another different set of lenses is responsible for the foveated region. The information can then be captured by different regions of the same sensor. In some case, a mobile mirror allows the foveated region to be moved across the field, but is still captured by the same region on the sensor. Even though the usefulness of such design has been shown, it is worth noting that the use of two optical channels will lead to an increase in overall cost and size.

Finally, foveated imaging can be achieved optically via a control of the local magnification across the field during the design [11-12]. Many parameters can be chosen as a mean to control the local magnification. One of them is the local focal length defined as the variation of the ray height on the image plane in relation to his origin in the field of view. By carefully adjusting the distortion, it is possible to image region of the field of view on larger area of the sensor compared to other regions of the field of view that are of the same size. However, this enhancement will be at the expense of the other regions as a consequence of having a finite sensor area. In other words, the area under the curve of the local focal length versus the field of view will remain constant. Unlike the SLM, the enhancement in that kind of design will be static and movement of the optical system will be necessary in order to precisely image objects outside this specific region. On the other hand, the foveating of the system at the optical level holds many advantages. The system is simple, containing only one optical channel and using nothing more complex than aspheric lens. The absence of need for computing power is also interesting. Indeed, the image will form on the sensor with discrimination over the quality of information across the field without the need for pixel binning or active phase element correction. Nevertheless, image correction algorithms can be used in order to reduce the effect of distortion and present to the viewer an image that is closer to what the human vision is accustom to.

When considering the problem of reducing the size of wide-angle imager, it is important to define the quality of the desired optical information for the entire field of view [13]. In many applications, a non-uniform quality can be acceptable. In endoscopy, for example, low resolution images on the side of the field of view are enough in order to navigate and identify the surrounding of the region of interest. The center of the field of view has a different requirement that doesn't need to be applied to the entire field of view. In the case of a surveillance camera placed on the ceiling, a much better resolution is needed on the sides in order to identify object farther away than right underneath the system. Taking into account this kind of information contributes significantly to the simplification of an optical system, especially in the case of wide-angle lens. Aberration correction being quite challenging for high field of view, a lower target resolution can result in a direct diminution of the number of lens needed.

In order to use efficiently foveated imaging to reduce the number of lens in an optical system, it is important to understand what are the compromises involved. An analysis of the solution space for a specific optical system is presented in this proceeding. The main goal is to assess the trade-off between the resolution across the field of view and the diminution in size of the system, principally through the removal of a lens. To achieve this goal, a comparison of different variations of the design with specific resolution target will be presented. The limits of the technique will also be discussed.

2. DESIGN PRESENTATION

The original design used is a state of the art miniature wide-angle lens, as presented in Figure 1. The design contains 6 lenses plus an IR filter. The design is balanced in order to provide a good resolution across the entire field of view. As stated in [1], many components of the design, like elements thicknesses and perturbations tolerances, are at the limit of manufacturer's capability today.

In order to study possible trade-off for miniaturization and foveating of the design, a second design was generated from the 6 lenses design. This second design, as presented on Figure 2, possesses 5 lenses (1 lens was removed) and no new degrees of freedom were introduced. The overall length was also reduced from 3.8 mm to 3.2 mm. Specific characteristics of the system like the f/# and the minimum relative illumination were preserved. In those conditions, it is inevitable that a substantial quality loss will be noticeable trough the design. However, through the use of foveated imaging, a certain control over the region of the field of view that will be the most affected will be possible.

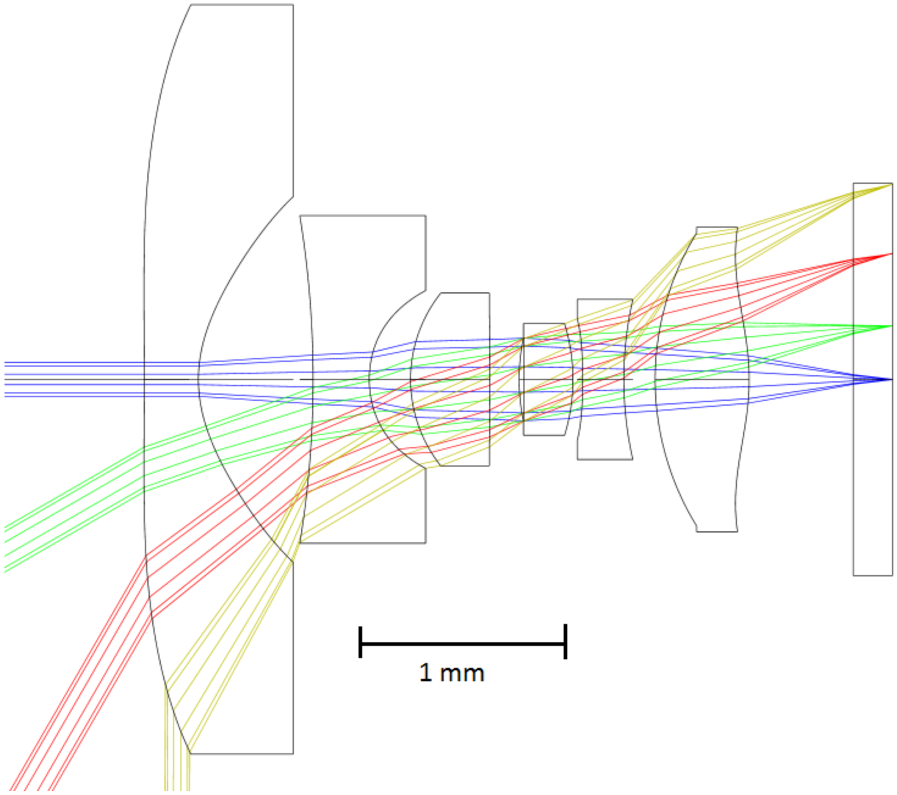

Figure 1. Layout of the miniature wide-angle lens. The total track length is 3.80 mm and the total number of lenses is 6 without the IR filter.

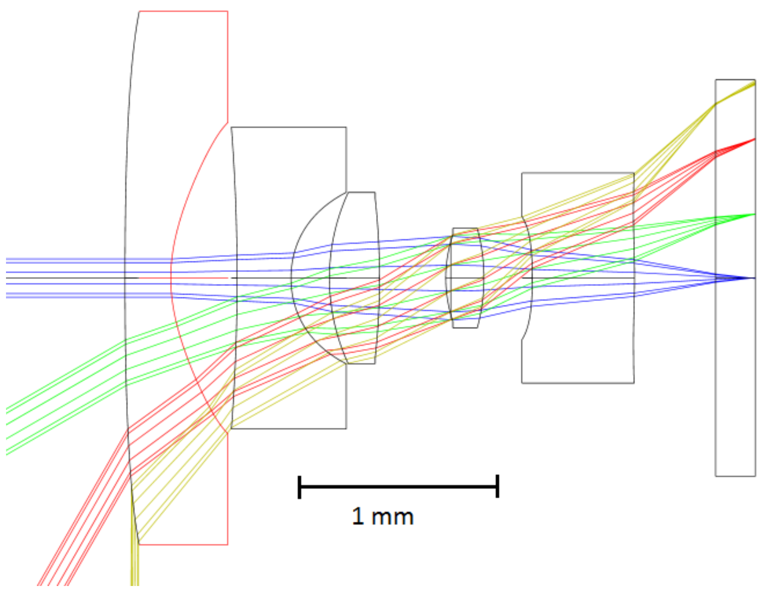

Figure 2. Layout of a 5 lenses version of the miniature wide-angle lens. The total track length is 3.20 mm.

3. RESULTS

The first step was to generate 4 designs for each lens configuration: the 6 lenses configuration and the 5 lenses configuration. Each of those designs was optimized to present different level of foveated behaviour by allowing the region of the sensor assigned to a specific field of view to change. This could be done by adjusting the distortion profile of the lens. The precise target used was the variation of image height H with respect to the field of view θ (dH/dθ). This quantity is directly proportional to the pixel/° count on one axis. A direct pixel count was not given so as to keep the exact sensor size and pixel size variable. The behaviour of each design is presented in Figure 3.

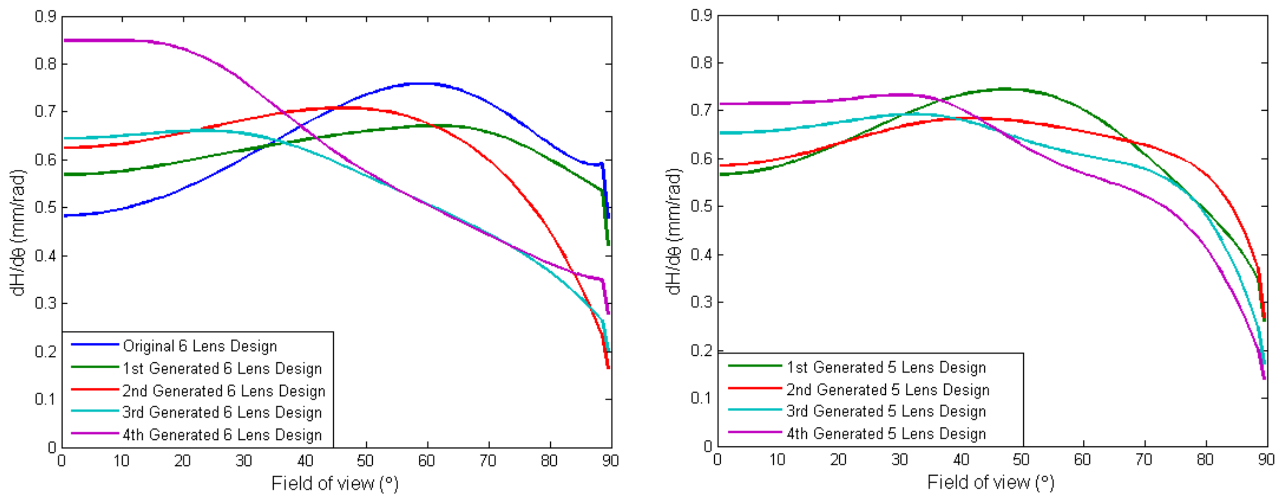

Figure 3. Variation of the image height H with respect to the field of view. On the left, the behaviors of the designs containing six lenses are presented. On the right, designs with only 5 lenses are presented. The emphasis on the center region of the field of view grows with the reference number of the design. The quantity dH/dθ is directly proportional to the pixel/° count on one axis.

By looking at Figure 3, it is apparent that the original 6 lenses design intended to diminish the number of pixels allowed in the center region in order to increase the image quality at higher field of view. The quantity dH/dθ being proportional to the pixel/° count, the curve is flattened for the 1st generated design, leading to and almost constant pixel/° count. For the subsequent 6 lenses designs, the tendency in inversed and a wider part of the detector is allocated to imaging the center of the field of view. As for the 5 lenses designs, also visible in Figure 3, the 1st generated design already has a smaller pixel/° count for the outer field of view. In light of the reduced degrees of freedom resulting from the removal of a lens, image quality at the edge of the field of view had to be lowered in order to preserve a certain quality in the center region. As it was the case for the 6 lenses designs, the balance of pixel/° shift more towards the centre region with each design. In addition to the pixel distribution, the quality of the MTF was also analysed for each design.

Two regions were selected for analysis: the 0° to 30° and the 60° to 90° regions. The quality of the MTF, expressed in cycles/mrad, was monitored in those regions. These units were selected because they provide a better understanding of what will be possible to identify in object space compared to cycles/mm, where the information given lies in the image space. The objective for the 6 lenses designs was to improve the quality of the MTF for the center region by devoting more pixels to it and to assess the cost paid in outer field of view quality. This of course led to a drop of the pixel count for other region of field of view. Even while trying to maintain a good quality in those remote regions as well, a certain quality lost was inevitable. In the case of the 5 lenses designs, the goal was to match the image quality of the 6 lenses designs in the center region of the field of view and also to assess the image quality loss in the outer field of view. Aside from the removal a lens, the total track length of the 5 lenses designs was also reduced by 0.6mm, which is 1/6 of the original design's length. The results are presented in Figure 4.

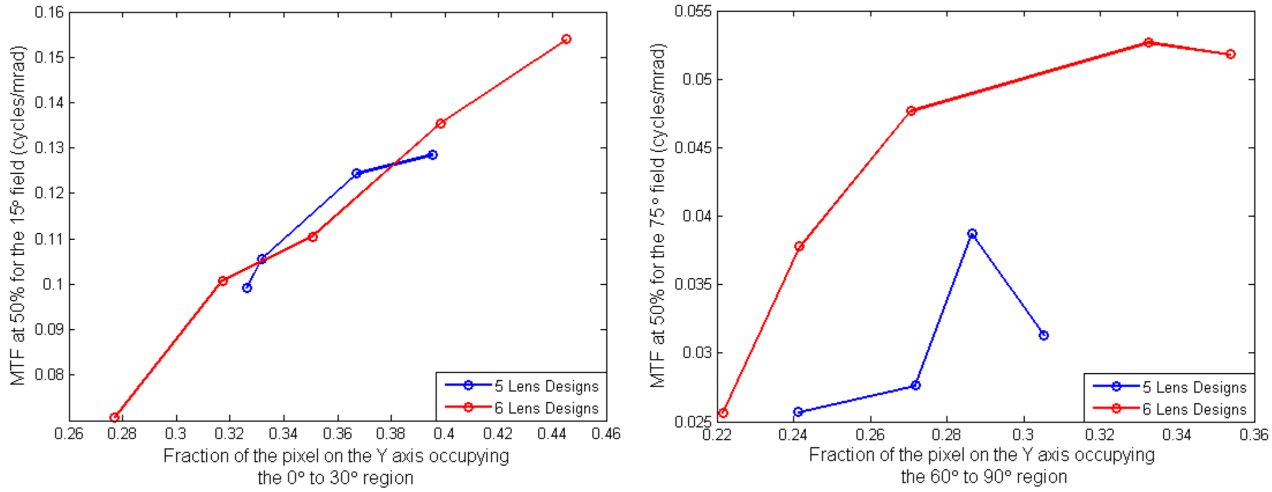

Figure 4. On the left, the quality of the MTF at 50% for the center region of the field of view for different pixel allocation. On the right, the quality of the MTF at 50% for the outer region of the field of view for different pixel allocation. In the case of the 6 lenses designs, the original design was included. On the left, the original design is represented in red as the leftmost marker. On the right, it is represented in red as the rightmost marker.

It is apparent from Figure 4 that a direct control over the distribution the image quality across the field of view was possible via the use of foveated imaging. In the case of the 6 lenses designs, the additional length and degree of freedom contributed a lot while trying to maintain a good MTF in the outer field of view, even if the number of pixel in the center region was increased. However, even if the quality of the MTF in the 60° to 90° region was reasonably maintained for a 10% pixel loss, the subsequent drop shows that the cost for increasing resolution in the centre region grows faster as the pixel count diminishes. In the case of the 5 lenses designs, the effort was oriented toward keeping a similar resolution to the 6 lenses designs in the center region, while reducing the overall length. However, this was accomplished at the cost of a 20 to 30% drop in image quality for the higher field of view compared to the 6 lenses designs.

4. CONCLUSION

This proceeding reported an analysis of the solution space for the simplification of a specific miniature wide-angle lens through foveating. It was shown that the image quality of the center region of the field of view could be enhanced via foveating in the case of the 6 lenses design. The parameter used in order to increase the number of pixel/° allowed in a specific region was a direct control over the variation of the image height H with respect to the field of view θ (dH/dθ). It was also shown that it was possible to maintain a similar image quality in the centre region of the field of view after the removal of one lens and a reduction of 1/6 of the total length using the same technique. In both a case, a degradation of the image quality in the outer field of view was inevitable. For designs with specific image quality requirement across the field of view, the use of foveated imaging is a valid approach in order to simplify optical system.

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