Consumer Electronic Optics: How small a lens can be? The case of panomorph lenses

Simon Thibault*[a,b], Jocelyn Parent[b], Hu Zhang[b], Xiaojun Du[b] and Patrice Roulet[b]
[a]COPL, Université Laval, Québec, Canada
[b]ImmerVision, 2020 University, Suite 2320, Montréal, QC, Canada, H3A 2A5

ABSTRACT

In 2014, miniature camera modules are applied to a variety of applications such as webcam, mobile phone, automotive, endoscope, tablets, portable computers and many other products. Mobile phone cameras are probably one of the most challenging parts due to the need for smaller and smaller total track length (TTL) and optimized embedded image processing algorithms. As the technology is developing, higher resolution and higher image quality, new capabilities are required to fulfil the market needs. Consequently, the lens system becomes more complex and requires more optical elements and/or new optical elements. What is the limit? How small an injection molded lens can be? We will discuss those questions by comparing two wide angle lenses for consumer electronic market. The first lens is a 6.56 mm (TTL) panoramic (180° FOV) lens built in 2012. The second is a more recent (2014) panoramic lens (180° FOV) with a TTL of 3.80 mm for mobile phone camera. Both optics are panomorph lenses used with megapixel sensors. Between 2012 and 2014, the development in design and plastic injection molding allowed a reduction of the TTL by more than 40%. This TTL reduction has been achieved by pushing the lens design to the extreme (edge/central air and material thicknesses as well as lens shape). This was also possible due to a better control of the injection molding process and material (low birefringence, haze and thermal stability). These aspects will be presented and discussed. During the next few years, we don't know if new material will come or new process but we will still need innovative people and industries to push again the limits.

Keywords: Miniature lens, panomorph lens, plastic lens.

1. INTRODUCTION

Small lenses, small camera modules are becoming integral in our daily lives. We find them in our mobile phones, tablets, laptops, wearable's devices, home entertainment systems, surveillance cameras, and much more. For many existing product applications, size reduction of the lenses and modules is crucial. The new generation of panomorph lenses meets the current needs, as well as opening the door to the development of new fields and applications that were not yet in existence.

The patented panomorph technology [1] combines a new generation of wide-angle lenses, magnifying zone of interest, and distortion correction algorithms (dewarping algorithm). Miniaturizing this technology ensures adoption by the consumer electronic industry, in particular the mobile device sector.

The aim of this paper is to answer the following question; how small can a panomorph lens be? In part 2, we will explore the miniaturization progress from 2011 to 2014. Then in part 3, future possible reductions in size using different optical design techniques will be reviewed. Part 4, will conclude by elaborating on applications of miniature panomorph technology embedded in current and next-generation mobile consumer devices.

2. FROM SMALL TO MINIATURE PANOMORPH LENSES

Between 2011 and 2014, significant efforts were put into reducing as much as possible the size of panomorph lenses. This resulted in a reduction of TTL from 6.56 mm for lens A as seen in the layout at Fig. 1 to a TTL of 3.80 mm for lens B as seen in the layout at Fig. 2. To achieve this reduction of 2.76 mm of TTL, compressions were done on all fronts, including total element thickness, air space thickness, IR filter and cover-glass thickness and in the back focal length. Table 1 summarizes the dimensions changes from lens A to lens B. 51% (1.41 mm) of the overall 2.76 mm

Current Developments in Lens Design and Optical Engineering XV, edited by R. Barry Johnson,
Virendra N. Mahajan, Simon Thibault, Proc. of SPIE Vol. 9192, 91920H · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2062418

reduction is due to the central element thickness, while 49% (1.35 mm) is due to the central air thickness. The 1.35 mm reduction in air space also includes a reduction of 0.27 mm in the back focal lengths.

A direct consequence of reducing the total track length of a panomorph lens is the reduction of the front element diameter. As seen table 1, a reduction by a ratio of 1.726 of the total length had as a consequence a reduction by a ratio of 1.748 for the front diameter. Because the air spaces, element central and edge thickness and the BFL are all within the current manufacturing limits, the question of panomorph lens size reduction could be is explored in the next section.

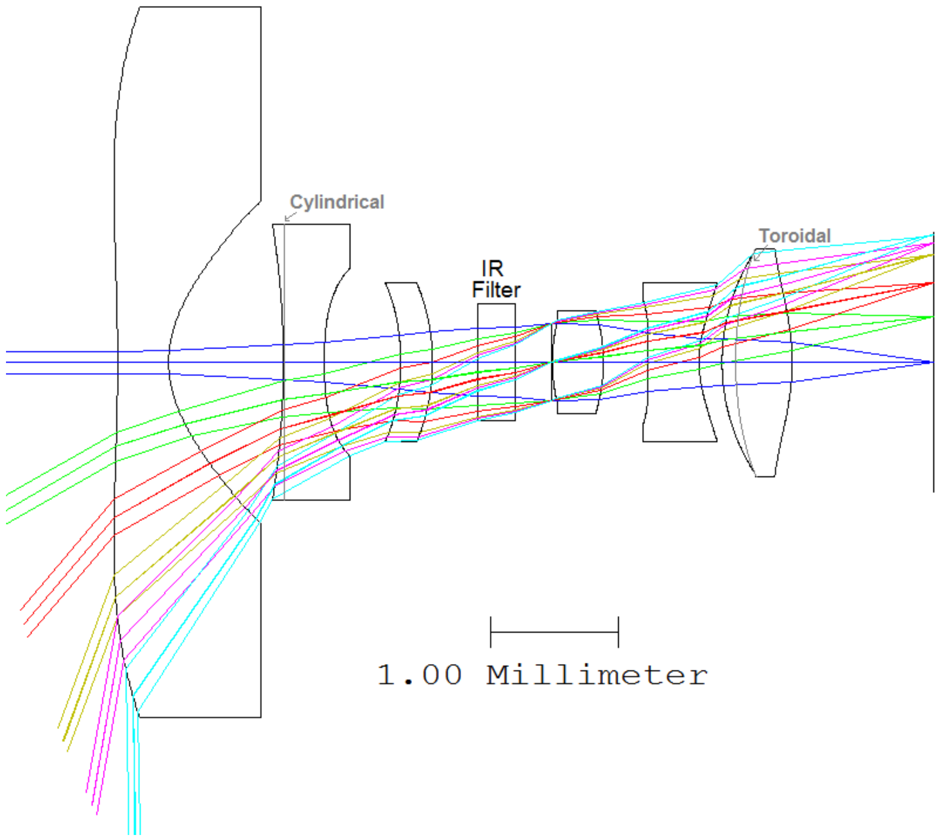

Figure 1. Layout of panomorph lens A with a TTL of 6.56 mm.

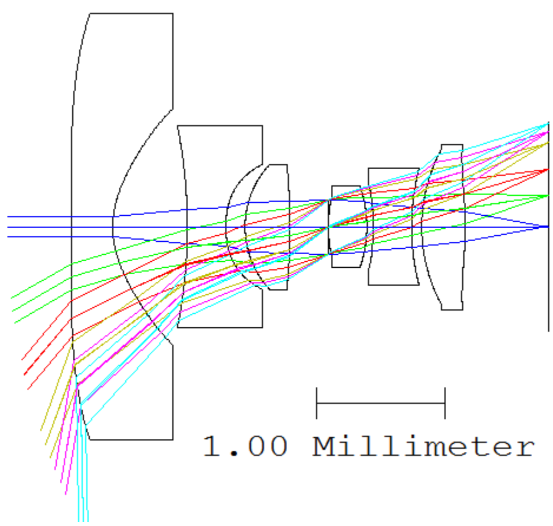

Figure 2. Layout of panomorph lens B with a TTL of 3.80 mm.

Table 1. All important dimensions had to be reduced to go from a TTL of 6.56 mm to a TTL of 3.80 mm.

Item	Lens A	Lens B	Difference	A/B ratio
Length dimensions				
Sum of central thickness of optical element	3.54 mm (including 0.44mm CG and 0.3mm IR)	2.13 mm (including 0.2mm IR)	-1.41 mm	1.663
Sum of central air space, including BFL	3.02 mm	1.67 mm	-1.35 mm	1.806
Total track length	6.56 mm	3.80 mm	-2.76 mm	1.726
Other dimensions				
Back focal length (in air)	0.92 mm	0.65 mm	-0.27 mm	1.411
EFL	0.561	0.484	-0.077 mm	1.159
Front surface diameter	6.80mm	3.89mm	-2.91 mm	1.748

3. REDUCING SIZES IN THE NEAR FUTURE

Reducing the size of a lens, as complex as it is, relies mainly on a scaling-down approach. However, to achieve a very small form factor, the scale-down is not always possible. We can notice in the table 1 that the EFL has been scaled by ≈ 1.2 and the TTL was by 1.73. This indicates a non pure or linear scale-down, given that every geometrical dimension will be scaled with the EFL (including the image plane). The air and central thicknesses are the most important dimensions. Having shorter air spaces and thinner lenses will be one of the principal approaches to reduce the lens TTL. Consequently, the manufacturing designs and processes, as well material thickness become a limiting factor.

Most manufacturers aim at reducing the minimum central thickness of optical elements. For example, new Zeonex® K26R can be molded to 0.2 mm without encountering any problems with weld lines, as is the case for most common plastic materials (COC, other Zeonex…). New manufacturing techniques from Nalux (www.naluxoptical.com) produce ultra-thin and large molding areas thickness to 0.1 mm. Lens B, as described above was limited to a central material thickness of about 0.3 mm. Does this mean we can reduce it down to 0.1 mm - by a factor of 3? Perhaps, if the image can be scaled by a factor of 3 (but detector size is limited). Another factor to consider is the edge thickness. To ensure that the plastic will flow through the lens, the edge must be minimal or as large as the central thickness limits.

Fig. 3 shows various lens shapes that can be found in miniature optics. If we define the central or edge thickness by 't', we can determine that the biconvex lens will have a central thickness larger than 't', maybe up to 3t. The biconcave lens will have a minimum central thickness of't' and an edge of 3t. We also found 'W type' lens, in this case, the total lens thickness will be about 2t. As for the meniscus, it can vary depending on the shape, but we can assume that the overall element thickness should be about 2t. If a camera phone lens using three lenses (mega pixel lens) is composed of a biconvex, a biconcave and a 'W type' lens, the total lens thickness would be about 3t+3t+2t = 8t. In this situation, adding air space (2t) and the BFL (2t for the filter) is suggested. Consequently, in this last scenario, the minimum TTL will be about 12t. If t=0.3 mm, the TTL is about 3.6 mm and 1.2 mm if t=0.1 mm. As per the data above, given that lens B has 6 elements within 3.80 mm, it is clear that this calculation is not exact! Achieving a thickness lower than 1 mm presents challenges with standard manufacturing techniques. Note that, we ascertain it is possible to further reduce the size of lenses by using new imaging techniques, using less lenses or using the lenses differently.

An additional obstacle to be considered is tolerances. Currently, producing a lens with a tolerance on the central thickness area smaller than 5-10 µm by injection molding is not achievable. The following equation (1) provides how the lens power (EFL) will be affected by a change in element thickness. R1 and R2 is the radius of curvature, Δt is the thickness tolerance and n the index of refraction. As the impact is relative to R1 and R2 magnitude, it can be small but if Δt is 10% of the lens thickness, the contribution of the thickness t on the lens power can change by 10% - which is far from a 1-2% tolerance on stock lenses.

$$\Delta\phi = \left[\frac{\Delta t \cdot (n-1)^2}{n \cdot R1 \cdot R2}\right] \qquad (1)$$

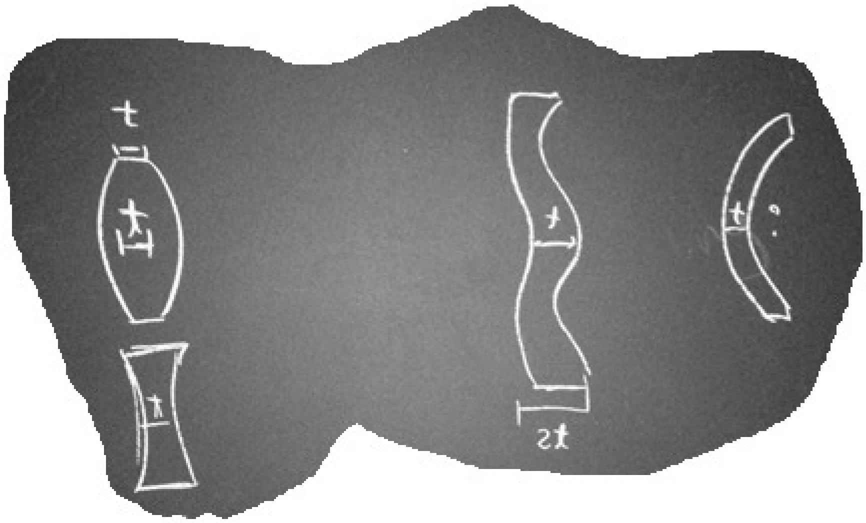

Figure 3. Various lens shape.

To reduce the number of elements, GRIN plastic technology an innovative approach is currently being explored by different teams [2-3].The variety plastic material available limits color correction (lateral color). Using radial GRIN materials, we can design a single element achromat that may help to reduce the number of component and the TTL. Current exploration of new techniques aims to reduce the lens dimensions, which includes computational imaging combining both hardware and software. Some examples are muli-aperture [4], wavefront coding (lens design simplification) [5] and plenoptics imaging systems.

4. APPLICATIONS OF MINIATURE PANOMORPH LENSES

The main advantage of panomorph camera is the full coverage of 360° field of view. Everything in front of a panomorph camera can be captured, which provides more content for different applications.

The panomorph lenses, described in this article, provide wide field of view (182° FOV) enclosed within a small form factor which fits directly onto smart phones, as well as many types of consumer electronic devices. In addition, another differing factor of panomorph lenses is its magnifying capability within a specific area of interest (zoom factor). This patented feature increases the pixel coverage (pixel/°) where it is optimal for the application and opens new possibilities for consumer electronics industry.

By replacing the mobile device front facing camera module, combining the panomorph lens with a state of the art sensor, numerous new applications become possible. Images recorded and processed by a dewarping algorithm, distortion correction processing and projections are applied to create multiple different images from the 360° contents.

The most popular mobile phone camera application is with no doubt the "selfie", made famous during last year's Oscar's. Front facing panomorph camera modules would capture more people and background than a regular narrow angle module. This can be seen in the example of Fig. 4. Some of the benefits include additional background information and a more aesthetically pleasing picture.

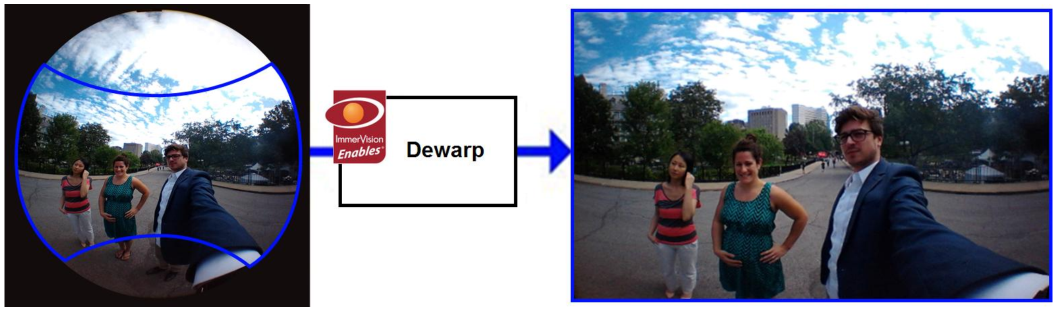

Figure 4: Selfie picture captured by the 3.80 mm panomorph lens and one example of a resulting dewarped image.

Another popular application of mobile phone camera is the video chat. A panomorph front facing camera would capture the entire audience located in front of or all around the camera. This wide FoV lens ensures that the person in front of the device is always seen by the camera. This can be seen in the example of Fig. 5. The video chat becomes much more comfortable and natural, thus allowing users to place their smartphone or tablet on their knees, on the side, on their desk…ensuring that video communication is continuous. Combined with a face tracking and image stabilization algorithm, the user can even walk, move, run with his device during the video call without paying particular attention if he is "seen" by its camera.

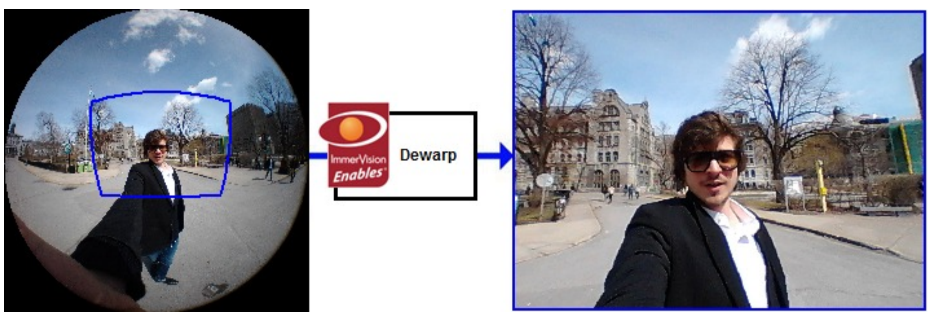

Figure 5: One to one video chat picture captured by the 3.80 mm panomorph lens and one example of a resulting dewarped images.

A natural extension of this use case is the one to many, or many to many video chat. In this case, the panomorph lens records all people seated in front or all-around of the device and the video chat application extracts, dewarps and transmits the different interlocutors dewarped video to the recipients. As shown in Fig. 6, the camera captures the image of four individuals around the device. This image is dewarped by an algorithm to display the four individuals in separate windows. Thus, the device becomes a portable video conference solution – individuals can move around, present or draw figures on the board know their actions will be recorded and shared.

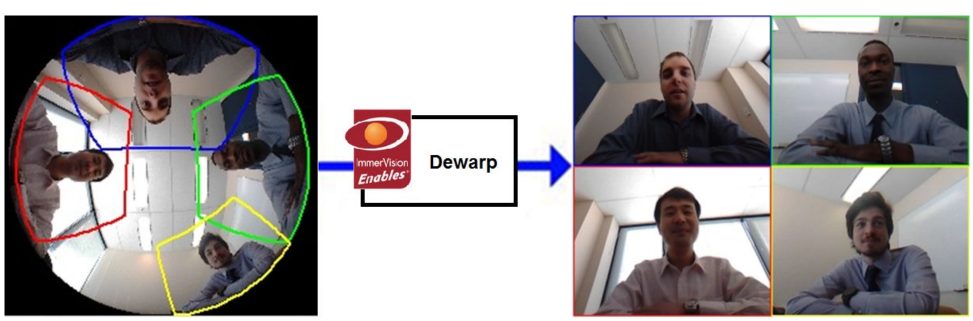

Figure 6: Many to one video-chat picture captured by the 3.80 mm panomorph lens and one example of 4 resulting dewarped images.

An additional feature is navigation in the image or video. This feature enables users to select and look at specific area within the 360° environment. Again combined with a face or sound tracking algorithm, the video chat application automatically focuses on the different people.

This new generation of device can record 360° panoramic images or videos instantaneously. In comparison, legacy panorama photo apps require the smartphone users to "pan" the device. Panomorph camera modules captures in real time 360° pictures or videos offering dynamic, living images.

This new type of panoramic content open a wide range of possibilities in real estate (virtual tours) and virtual reality (VR), surveillance, wearable, sport-camera and e-learning applications.

VR has garnered much attention in the consumer marketplace [6]. VR mask, such as Oculus Rift or Sony Morpheus, displays stereoscopic 360° environment to user, giving an immersive feeling to the user. Currently, multiple devices are developed to capture 360° video for such VR devices. A smartphone with a panomorph camera module will become the most popular and convenient way to provide abundant VR content.

In the surveillance sector, small panomorph camera modules can be used within remote units placed strategically to monitor a baby, children, a specific location, a vehicle or the general surrounding, etc. Afterwards, users can easily review and monitor their environment in 360° by obtaining the images saved locally or onto a cloud service.

For wearable applications, the panomorph camera module enhances the field of vision of devices like glasses, law enforcement cameras, etc. These large field of view, combined with dewarping and image stabilization algorithms, record and display in real time the full action in front of the device independently of the camera movements done by the holder during the capture.

Action or sports camera has grown in popularity and has seen its market share increased rapidly in the past few years [7]. Because action cameras follow unpredictable movements of the carrier (surfer, biker, snowboarder, etc.), a 360° panomorph lens will ensure that a full 360° environment and action moment is recorded. Dewarping, post processing combined with device orientation sensors and image stabilization algorithms allow 360° navigation, displaying and sharing of stable image contents. This type of technology definitively increases the value of actions cameras.

In the past 2 years, e-learning has dramatically increased. The ability to record and share a 360° environment instead of only a pinhole view of a scene increases the ease of sharing crucial knowledge, experience and expertise across distances.

In summary, this new generation of miniature panomorph lens will be embedded onto a multitude of devices such as smartphones, tablets, laptops and wearables. This will ensure the recording and sharing of 360°enviroment across platforms quickly and effortlessly. The dewarping process takes part of the image processing pipeline within the device operating system (OS), thus allowing developers to create a multitude of applications.

5. CONCLUSION

The reduction in size of panomorph lens between 2011 and 2014 was due to pushing to cutting edge designs and manufacturing processes. This approach has pushed the limits of manufacturing capabilities for central and edge thickness as well as air spaces. In order to achieve significant reduction of sizes, new manufacturing capabilities, fewer elements or new imaging techniques must be used. At present, the 3.80 mm panomorph lens is the smallest 180° panomorph lens and opened the door to many new applications and devices. We will continue to push the limits of lens design and manufacturing techniques in order to develop smaller multi-megapixel miniature panomorph lenses.

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