Photonics-enhanced smart imaging systems
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ABSTRACT

We discuss different photonics-enhanced multichannel multiresolution imaging systems in which the different channels have different imaging properties, namely a different FOV and angular resolution, over different areas of an image sensor. This could allow different image processing algorithms to be implemented to process the different images. A basic three-channel multiresolution imaging system was designed at 587.6 nm where each of the three channels consist of four aspherical lens surfaces. These lenses have been fabricated in PMMA through ultra-precision diamond tooling and afterwards assembled with aperture stops, baffles and a commercial CMOS sensor. To reduce the influence of chromatic aberrations, hybrid lenses, which contain diffractive surfaces on top of refractive ones, have been included within the previous designs of the three channels. These hybrid lenses have also been fabricated through ultra-precision diamond tooling, assembled and verified in an experimental demonstration. The three channels with hybrid lenses show better image quality (both in the simulation and experiment) compared to the purely refractive three channel design. Because of a limited depth of field of the aforementioned multichannel multiresolution imaging systems, a voltage tunable lens has been integrated in the first channel to extend the depth of field of the overall system. The refocusing capability has significantly improved the depth of field of the system and ranged from 0.25 m to infinity compared to 9 m to infinity for the aforementioned basic three-channel multiresolution imaging system.

Keywords: lens system design, imaging sensor, photonics-enhanced, multiresolution, modulation transfer function, rapid prototyping

1. INTRODUCTION

Multi-channel imaging systems become a good alternative to single channel bulky imaging systems for different applications such as machine vision and security medical imaging because of their low-form factor and excellent performance-to-cost ratio. These imaging systems are inspired by the natural insect compound eyes which consist of arrays of microlenses and photoreceptors on a curved surface. A combination of a microlens and a photoreceptor forms one channel which captures only a part of the total field-of-view (FOV). As a result, the compound eye is able to capture a wide FOV in a small volume\textsuperscript{1-7}.

Researchers adopted several approaches to realize artificial compound eyes. Duparré J. et. al. demonstrated an artificial compound eye consisting of a stack of a microlens array and a photodetector array on a planar surface. The microlens array was fabricated through lithographic techniques at wafer scale and assembled with a photodetector array which has a different pitch than the microlens array. This enables each microlens to image a separate view direction such that the overall system acquires a wide FOV\textsuperscript{6}. In another approach, Li L. et. al. demonstrated a 3D artificial compound eye which comprises of a micro-prism array arranged on a hemisphere and a planar micro-lens array designed for a wide FOV. The micro-prism array changes the direction of rays originating from off-axis angles to on-axis direction so that they can be focused by the planar microlens array to the image sensor\textsuperscript{8}. The microlens and micro-prism arrays were fabricated with ultra-precision diamond machining and turning techniques. The artificial compound eye was further miniaturized by combining the functionalities of the micro-prism and the micro-lens. The same researchers realized a planar free-form microlens array which at the same time deflects and focuses the rays to the image sensor. In another approach Floreano D. et.al. realized an artificial compound eye which resembled a lot of an arthropod (insect) eye. The microlens array and the photodetector array were arranged on a curved surface like a natural compound eye. This success was achieved because of the breakthroughs in elastomeric materials and the advancements of technology in flexible printed circuit boards. The microlens array was designed on a hemispherical shape and integrated with deformable arrays of silicon photodiodes which were able to be curved also to a hemispherical shape for obtaining a wide FOV\textsuperscript{9}. Driven by the continuous improvement
In the computing power of microprocessors and performance of image sensors, the images captured by artificial compound eyes are further processed to obtain highly resolved (super resolved) images. It is even possible to add light field imaging functionalities like offline refocusing and depth calculation in the artificial compound eye imaging systems. This in fact leads to miniaturized cameras with 3D imaging functionality to be integrated in portable devices such as smartphones.

In the above approaches, the demonstrated artificial compound eyes have similar imaging characteristics such as focal length, FOV and angular resolution. In contrast, we propose a different approach, where the different channels have been designed to have different FOV and angular resolution. Our approach is inspired by the visual system of a human eye, where it has the highest angular resolution at the fovea centralis and a lower resolution at the peripheral regions due to the uneven distribution of the cone receptors. In the past years, we designed and demonstrated a three-channel imaging system which contains multiple optical channels that have different angular resolution and central FOVs, such systems are called multichannel multiresolution imaging systems. The interesting aspect of this concept is that it opens up an opportunity to perform image processing tasks locally, which means different image processing algorithms can be implemented on the different regions of an image sensor. For example, a motion detection algorithm could be applied on the image sensor segment of the wide FOV channel, whereas a face detection algorithm could be deployed on that of the high resolution channel. Multichannel multiresolution imaging systems are able to have cognizance of a large area with the wide FOV channel while inspecting the details of a certain region of interest with the highest resolution channel. This paper reviews our work in the design and demonstration of a multichannel multiresolution imaging system, chromatic aberration reduction in such systems using hybrid lenses and addition of refocusing functionality in the system using voltage tunable liquid lenses.

This paper is structured as follows. In section 2, the design and proof-of-concept demonstration of a three-channel multiresolution imaging system is discussed. The reduction of chromatic aberration in a multichannel imaging systems using hybrid lenses is included in section 3. Section 4 describes the design and proof-of-concept demonstration of a multiresolution refocusing imaging system. The conclusions and summary of this paper are found in section 5.

2. DESIGN AND PROOF-OF-CONCEPT DEMONSTRATION OF A THREE-CHANNEL, MULTI-RESOLUTION IMAGING SYSTEM

2.1 Design of the imaging system

The main goal of our design is to realize a single imaging system that has three optical channels with different imaging properties (FOV, angular resolution and focal length). Each optical channel contains four aspherical lens surfaces, an aperture stop and a baffle which is used to prevent possible crosstalk among the neighboring channels. The imaging system is designed at a wavelength of 587.6 nm using Code V, commercial optical design software. The material out of which the lenses are fabricated is PMMA.

(a) (b)

Fig. 1. (a) Image sensor division among the three channels. (b) Three-channel, multi-resolution imaging system.

The three optical channels segment an image sensor with 1440 x 960 pixels (of 10 μm pixel size) as shown in Fig. 1 (a). The largest area of the sensor is dedicated for the wide FOV channel whereas the rest of the image sensor is equally shared by the remaining two channels. This way of segmentation of the image sensor contributes to have a large FOV and resolution ratio between the channels with extreme properties. The first optical channel has the narrowest FOV (2x3.5°)
and the largest angular resolution (0.0096°). Whereas, the third optical channel possesses the widest FOV (2x40°) and smallest angular resolution (0.078°). On the other hand, the second optical channel has intermediate properties, i.e., FOV of 2x10° and angular resolution of 0.029°. The design layout of the three-channel imaging system with the aperture stops and baffle is shown in Fig. 1(b). The design contains out of two lens plates each containing three lenses, one for each channel. The assembly of the components can be accomplished using alignment holes and guiding pins. The overall dimension of the system is about 15 mm x10 mm x47 mm.

2.2 Proof-of-concept demonstration of the imaging system

Once the design of the imaging system was finished, the lenses of the different channels were fabricated in PMMA by ultra-precision diamond tooling. The lenses were fabricated on four plates where each plate contained three lens surfaces. The aperture stop and the baffles were manufactured from a metal alloy (alloy of Titanium (Ti) and Aluminum (Al)) by metal additive manufacturing. Afterwards, the fabricated lens plates were assembled with the manufactured aperture stop plate and baffle using alignment holes and guiding pins. The complete imaging system was built up by integrating a commercial CMOS sensor with the assembled components (see Fig. 2a).

The three-channel imaging system was then experimentally tested by capturing images. An object was imaged by the three channels at the same time with different FOV and angular resolution. The experimental and simulated images are shown in Fig 2b/c. Both the experimental and simulated images show the multiresolution nature of the imaging system where the first channel images only a small portion of the object at high resolution (larger magnification) than the third channel which images the whole object at low resolution. In the image captured by the third channel, color fringes are noticed across its edges due to chromatic aberrations. The ratio of magnification of the first channel to the second channel is approximately 3 and the ratio of magnification of the second channel to the third channel is about 2; this results in a magnification ratio of about 6 between the first channel and the third channel.

Compared to the simulated images (see Fig. 2b), the quality of the experimental images is lower. This is due to misalignment problems, as there is almost no freedom to make the image distance precisely accurate. This is a practical limitation we had. In addition, even though the tube reduces the crosstalk between the channels, there is still crosstalk between the channels. For a successful decoupling of the three channels, their light paths should be completely separated along the entire light path of the channels. The crosstalk is noticed across the border between the neighboring channels; for example, the cross talk between the first and second channels is noticeable in Fig.2. Moreover, the tube is not totally absorbing; as a result, the diffused reflections (stray light) from its walls essentially reduce the contrast of the images. From the experimental results shown in Fig. 2, despite their low image quality compared to the simulated results, the captured images are able to prove the system’s behavior of having channels with different resolution and FOVs.

3. MAKING THE LENS SURFACES HYBRID TO REDUCE CHROMATIC ABERRATIONS

3.1 Design of the imaging system with hybrid lenses

The performance of the demonstrated three-channel imaging system was affected by chromatic aberrations as it was designed for a single wavelength of 587.6 nm. The effect of the chromatic aberrations are visible on the simulated and
experimentally captured images as shown in Fig. 2 (b) and (c). This is especially visible on the images simulated or captured through the third optical channel because of its wide FOV. The cause of the chromatic aberrations is the dispersion of the lens material. As a result the different wavelengths are focused at different axial or lateral positions in the image plane. As a result, the quality of the obtained image is deteriorated. The chromatic aberration caused by the longitudinal/axial defocus of the different wavelengths is called longitudinal chromatic aberration. On the other hand, the chromatic aberration caused by the lateral shift of an off-axis image point, from its paraxial position, for different wavelengths is called lateral chromatic aberration.\textsuperscript{13, 14} Chromatic aberrations can be compensated by hybrid lenses, which contain diffractive structures on top of the refractive surfaces\textsuperscript{12}, so that the overall system remains lightweight and compact. A diffractive surface has opposite dispersion characteristics compared to a refractive one, therefore the chromatic aberrations of a hybrid surface are reduced because the chromatic aberrations of the diffractive and refractive surfaces cancel each other. So, by incorporating hybrid lenses in the design of the three channels, chromatic aberrations of the three-channel imaging system is reduced\textsuperscript{15}.

The hybrid lens enables the three-channel multiresolution imaging system to operate in a wide spectral range. The imaging system is intended to operate in the visible domain of the electromagnetic spectrum. Hence, we have chosen three wavelengths, 486 nm, 587.6 nm and 656 nm to evaluate the performance of the optical channels with hybrid lenses. The chosen lens material is PMMA and the diffractive surface will be diamond turned on top of the refractive surface which subsequently results in a hybrid surface for correcting chromatic aberrations. The surface parameters of the refractive surfaces and phase coefficients of the diffractive surfaces are optimized to obtain a system with low monochromatic and chromatic aberrations. The optimization algorithm tries to minimize the aberrations as much as possible for the three wavelengths mentioned above. The diffractive surfaces are blazed at a wavelength of 587.6 nm.

The positions and designs of the diffractive surfaces for the three channels are different as they have different imaging characteristics. The performance of the first channel is mainly influenced by longitudinal chromatic aberration because of its relatively large aperture. Therefore, the diffractive surface is placed at the first surface as this surface is also acting as an aperture stop. The diffractive surface was designed at the first diffraction order and blazed at 587.6 nm. There are 5 Fresnel zones over the 4.4 mm full diameter of the surface. The smallest spacing between the zones occurs at the edge of the surface between the last two zones and is about 220 µm. The relief height (h) is determined by the wavelength (λ) and refractive index difference of air and the lens material (n), namely $h = \lambda / (n-1)$\textsuperscript{15} resulting in a relief height of 1.12 µm. The second optical channel has a wider FOV than the first channel as explained above. Therefore, the second optical channel is more influenced by lateral color aberrations than longitudinal color aberrations also because of its smaller clear aperture. This necessitates the diffractive surface to be superimposed on the last refractive surface which is far from the aperture stop and close to the image plane. The diffractive surface was designed at the first diffraction order and contains 13 Fresnel zones in the 4.6 mm full diameter of the surface. The smallest spacing between the zones is about 86 µm and occurs between the last two zones. The blaze height is 1.12 µm, analogue to the first channel.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{The hybrid surfaces of the (a) first optical channel, (b) second optical channel and (c) third optical channel (top tile) and the corresponding diffractive surfaces (bottom tile), designed in the first diffraction order (the first and second channels) and second diffraction order (the third optical channel). There are 5, 13 and 39 Fresnel zones, in the diffractive surface of the first, the second and the third optical channel respectively.}
\end{figure}
Because of its widest FOV, the third optical channel is more prone to the effects of lateral color aberrations. Therefore, the diffractive surface is placed on the last surface which is further away from the aperture stop and closer to the image sensor, to correct the lateral chromatic aberrations. However, due to manufacturing reasons, the diffractive surface was not designed on the last (fourth) surface but on the third surface which is relatively flat. To correct for the lateral color aberrations especially for large field angles, the spacing between the Fresnel zones of the diffractive surface needs to be very small as that enables to strongly deflect the rays. Fabricating a diffractive surface with very small features is difficult because of the high precision requirement of the machining process. One way of reducing the challenge of manufacturing is designing the diffractive surface at a higher diffraction order \(^{16-18}\). Therefore, we have designed the diffractive surface of the third optical channel at the second diffraction order which doubles the surface relief height, compared to the first and second channel. So, the surface relief height in this case is 2.24 \(\mu\text{m}\). There are 39 Fresnel zones in the diffractive surface in its full diameter of 7 mm. The smallest spacing, which occurs between the last two zones at the edge of the surface, is 50 \(\mu\text{m}\). The profiles of their diffractive and hybrid surfaces are given in Fig. 3 (a-c).

3.2 Performance of the three-channel multiresolution imaging system with hybrid lenses

The performance of the three channels was analyzed for a broad wavelength range by specifying 3 discrete wavelengths. For the first optical channel, three wavelengths (420 nm, 587.6 nm and 700 nm) were considered. For the second and third optical channel a smaller wavelength range was considered because of their wider FOV. Thanks to the hybrid lenses, the chromatic aberrations have been significantly reduced and the performance of the channels is found to be nearly diffraction limited. The chromatic aberrations present in the three optical channels are described using lateral color plots as shown in Fig. 4. The magnitudes of the lateral color aberrations present in the three-channels with and without hybrid lenses for the same wavelength range have been compared. In the first channel, as can be seen from Fig. 4 (a), the maximum lateral color is smaller than 2\(\mu\text{m}\), which is by far smaller than 10 \(\mu\text{m}\), the pixel size of the sensor. This means that the effect of the lateral color on the performance of this optical channel is negligible. On the other hand, for the corresponding optical channel without a hybrid lens, the lateral color is 14 \(\mu\text{m}\) (see Fig. 4 (a)). The same trend is also visible for the second and third optical channel, namely the designs that contain hybrid lenses are able to considerably reduce chromatic aberrations compared to the corresponding designs without hybrid lenses. The lateral color of the second optical channel with a hybrid lens is lower than 10 \(\mu\text{m}\), whereas that of the corresponding design without a hybrid lens is about 50 \(\mu\text{m}\), which corresponds to about 5 pixels of error. So, by including the hybrid lenses, the lateral color is reduced by about 40 \(\mu\text{m}\) (see Fig. 4 (b)). The third optical channel design without a hybrid lens has the largest lateral color aberration that ranges up to 250\(\mu\text{m}\) due to its wide FOV (see Fig. 4 (c)). Nevertheless, the hybrid lens was able to limit the lateral color to about 14\(\mu\text{m}\).

![Fig. 4. Lateral color plots of the three optical channels with hybrid lenses and their comparison with the corresponding lateral color aberration (magnitude) of the three optical channels without hybrid lenses, respectively. (a) first optical channel, (b) second optical channel and (c) third optical channel.](image)

The other quantitative parameter that has been used to evaluate the performance of the three channels is the MTF. The MTFs of the three optical channels with and without hybrid lenses are shown in Fig 5. The purple colored lines represent the MTF of the designs with hybrid lenses for on-axis and off-axis field angles, whereas the blue lines represent the MTF of the designs without hybrid lenses. The lines with circular marker (o) are for on-axis field angles, whereas the lines with asterisk (*) are for off-axis. From comparison of the MTF for the designs with and without hybrid lenses it is observed that the MTF of the system with hybrid lenses (on-axis, purple lines marked with circles) are significantly higher than the MTF...
of the corresponding system without hybrid lenses (blue lines marked with circles). And the same is true for off-axis field angles, i.e. MTF curves of the optical channels with hybrid lenses lie well above those of the respective optical channels without hybrid lenses. For the first optical channel, the MTF lines at different field angles are close together because of its narrow FOV; whereas for the second and third optical channels, the MTF curves of the off-axis field angles are well below those of the on-axis field angle as they have a wider FOV, especially this is true for the third optical channel. Moreover, the MTF of the second and third optical channels without hybrid lenses (for off-axis field angles) appear jagged and have ripples due to chromatic aberrations. This situation has been alleviated with hybrid lenses and it has been possible to obtain smooth MTF curves which are well above the corresponding MTF curves of the design without hybrid lenses. So, at this point we can confidently conclude that the hybrid lenses have significantly reduced the chromatic aberrations of the three optical channels with hybrid lenses and improved the overall performance compared to the corresponding designs without hybrid lenses.

Fig. 5. MTF of the three optical channels with hybrid lenses and their comparison with the corresponding MTF of the three channels without hybrid lenses. (a) first optical channel, (b) second optical channel and (c) third optical channel.

4. DESIGN AND PROOF-OF-CONCEPT DEMONSTRATION OF A MULTI-RESOLUTION REFOCUSING IMAGING SYSTEM USING A TUNABLE LENS

The multi-channel imaging system we have discussed above has limited depth of field (DOF) because of the large focal length of the first (high resolution) channel. To extend the depth of field of the system, refocusing functionality is added to the system by using a voltage tunable liquid lens (as traditional refocusing mechanisms are based on mechanical movements of the components and are too bulky to integrate into a miniaturized design). Therefore, a tunable lens is integrated with the first channel of the multichannel imaging system to improve its depth of field. By the introduction of the tunable lens, the limited DOF of the high resolution optical channel of the three-channel imaging system, going from 9m until infinity, was improved to a DOF going from 0.254m until infinity.

4.1 Design of a refocusing two-channel imaging system

As the DOF of the third (wide FOV) channel is large because of its small focal length, it does not need any refocusing functionality. Whereas, the design of the first channel is adapted by including the tunable lens to obtain a refocusing functionality and thus to extend its depth of field. Therefore, the total imaging system is composed of the wide FOV channel and the high resolution channel with a tunable lens, which effectively results in a two-channel imaging system. This could further miniaturize the system while not losing the multiresolution capability. An Artic 320 electrically tunable liquid lens of Varioptic11 was used for achieving the refocusing functionality. This tunable lens consists of two glass plates filled with a conducting watery fluid and a non-conducting oil solution. The interface between the liquids acts as a lens surface and changes it curvature by the application of a voltage because of the electrowetting effect\cite{18,19}. The model of the tunable lens was developed based on the parameters provided by the manufacturer’s datasheet, measurement data from previous publication and experimental characterization of the tunable lens\cite{20,21}. We used the tunable lens in its operation region from 50.4Vrms until 60.1Vrms. For applied voltages from 50.4Vrms onwards, the lens surface is clearly convex shaped and shows a hysteresis-free behavior. Moreover, within this operation range, the lens behaves diffraction-limited. In our design, the tunable lens is placed at the center between the two passive lenses, at the same relative position with the aperture of the wide FOV imaging channel. We preferred this central position, because this results in a robust, symmetric two-channel imaging design. The tunable lens can be mounted with the use of a planar absorbing sheet, containing a small aperture at the side of the wide FOV imaging channel and a larger hole at the side of the high resolution imaging channel,
allowing the fixation of the tunable lens. The final optimized two-channel imaging system with refocusing functionality is presented in Fig. 6.

![Diagram of imaging system](image)

Fig. 6. (a) Integrated CAD design of the optimized multi-resolution two-channel refocusing imaging system; (b) Wide FOV imaging channel; (c) High resolution refocusing imaging channel.

### 4.2 Performance of the refocusing imaging channel

To evaluate the DOF of the high resolution imaging channel, we simulated the image quality at the image sensor for different object distances (Fig.7). Comparing the simulated image quality of the static and refocusing high resolution imaging channel, we observe an enlarged DOF after the implementation of the electrically tunable liquid lens.

![Simulation results](image)

Fig. 7. Image quality of both the static (top) and refocusing (bottom) high resolution imaging channel, for different object distances.

### 4.3 Proof-of-concept demonstration of a voltage tunable refocusing imaging system

The two passive lenses of the refocusing channel were fabricated by ultra-precision diamond tooling and integrated with the tunable lens, a commercial CMOS sensor to demonstrate the proof-of-concept. The experimental set-up of the refocusing channel is shown in Fig. 8. The experimental performance of the refocusing system has been studied by measuring the optimal object distances, DOF, MTF and also visualizing the captured images at different object distances by varying the applied voltage. The optimal object distances and DOF for each applied voltage on the tunable lens were determined by the use of a USAF 1951 resolution chart. For each voltage, the measured and simulated optimal object distance and DOF (see Fig. 8 (right)) are in a good agreement with each other. For both the simulation and measurement, the DOF (indicated in the form of ‘error bars’ in Fig. 8 (right)) increases with increasing object distance and decreasing voltage.
Moreover, the experimental MTF of the refocusing channel was calculated using a slanted edge technique for different voltages. The slanted edge target was positioned at the corresponding optimal object distances and imaged by the refocusing imaging channel. The MTF has been calculated from the image of the slanted edge target by calculating the edge transfer function and eventually the MTF\textsuperscript{24}. This calculation was performed by using an image analysis software called ImageJ\textsuperscript{25}. For all voltages in the linear region of the tunable lens, a good correspondence between the simulated and measured MTF was obtained. For example, the simulated and measured MTF for 55 Vrms and 59 Vrms are presented in Fig. 9. The MTF at the other applied voltages showed the same behavior. The small deviations between the simulated and measured MTF are due to misalignment errors occurred during the experiment.

Finally, experimental images were recorded to visualize the performance of the refocusing imaging channel at different voltages. Fig. 10 shows the recorded images for two separate object positions at two voltage values (52 Vrms and 60 Vrms). At higher voltages, the closer object is in focus while at lower voltages the object positioned further away is in focus. This agrees well with the experimental and the simulation results (see Fig. 8). For each voltage, there is an optimal object distance that gives a sharp image. Conversely, for each object distance we can find an optimal voltage that gives a sharp image. The experimental results match well with the corresponding simulation results. When we placed the object at the object distances used in the simulations, a good image quality was obtained. If we then moved the object while
keeping the applied voltage constant, the image quality deteriorated. This could then be improved by changing the voltage to another value. The good agreement between the experimental and simulation results proved that tunable lenses can be used to realize a compact refocusing imaging system that has an extended DOF.

Fig. 10. Focusing of two objects which are at a distance of 3.2 m between each other using the refocusing imaging channel with a tunable lens: (left) front object is in focus at $V=60\,\text{Vrms}$ and (right) rear object is in focus at $V=52\,\text{Vrms}$.

5. CONCLUSION

We have designed and demonstrated a three-channel multi-resolution imaging system that can simultaneously capture images having different magnifications and FOVs on an image sensor. We tackled the inherent limitations of the imaging system such as narrow spectral range operation and limited depth of field by following different approaches. By using hybrid lenses, we expanded the operating spectral range of the multichannel imaging system in the visible domain. We have also designed and demonstrated a refocusing imaging system by using a voltage tunable lens to extend the depth of field of the system. By integrating the tunable lens with the first channel, the depth of field has been improved from 9 m to 0.25 m up to infinity. These achievements open up opportunities to realize miniaturized multifunctional imaging systems. In the near future, we will investigate other functionalities such as depth estimation in our imaging system.

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