

Design and implementation of a retina-like imaging system based on non-uniform lens array

Yue Liu¹, Yong Song^{*1}, Qun Hao¹, Tianle Tan^{2,3}, Chaozhen Liu^{2,3}, Zhuohuang Zhang¹

(¹ School of Optoelectronics, Beijing institute of technology, Beijing 100081, China

² Shanghai Institute of Spaceflight Control Technology, Shanghai 200233, China

³ Shanghai Key Laboratory of Aerospace Intelligent Control Technology, Shanghai
200233, China)

ABSTRACT

Retina-like imaging system is an imaging system with space-variant resolution similar to the photoreceptor distribution of primate retina. In this paper, the design and implementation of the retina-like imaging system based on non-uniform lens array has been introduced. Firstly, the mathematical model of the non-uniform lens array is deduced. Secondly, the hardware design of the proposed system is discussed in detail, which includes the photodetectors array, current-voltage conversion circuit, ratio normalization circuit and A/D converter circuit, etc. Furthermore, the design of the corresponding software is also discussed. Finally, the corresponding experiments have been carried out. Our results show that the developed system has the characteristic of rotation and scaling invariance property, which will help to result in a new retina-like image sensor with the characteristics of high speed, high resolution, high sensitivity and big planar array, etc.

Key words: retina-like sensor; non-uniform lens array; log-polar mapping; non-uniform sampling; FPGA

1. INTRODUCTION

Retina-like image sensor is an image sensor with the space-variant resolution similar to the photoreceptor distribution of primate retina^[1]. In this retina-like image sensor, photodetectors are arranged over concentric rings, while the sizes of photodetectors increase monotonically along radial line from center to peripheral region. Compared with the conventional image sensor with space-invariant resolution^[2,3], retina-like image sensor has comparatively fewer output data, thereby increasing the speed of image acquisition and process. On the other hand, retina-like image sensor can transfer an image from Cartesian coordinate system to log-polar coordinate system, which results in an important characteristic of special rotation and scaling invariance property^[3].

Previous research on the retina-like image sensor mainly focused on the sensor based on space-variant pixels, in which pixels of different sizes were generated and arranged on the basis of CCD (Charge Coupled Device) or CMOS (Complementary Metal Oxide Semiconductor) technology^[3,5]. However, this type of retina-like image sensor has several disadvantages: 1) Low speed. In order to achieve high resolution, the distance between two neighbor pixels of this kind of retina-like image sensor is limited. As a result, it cannot provide enough space for signal output channels, thereby results in the limitation of signal output rate; 2) Low sensitivity. Due to the pixel size of the sensor based on CCD or CMOS technology is generally very small, which results in poor sensitivity^[6,7]. Additionally, the crosstalk among neighbor pixels also brings additional noise and decreases the sensitivity; 3) High cost. All the space-variant pixels are generated and arranged by using CCD or CMOS technology, resulting in complexity and difficulty of sensor design as well as comparatively high cost.

To solve the above problems, we proposed a retina-like imaging system based on space-variant lens array in this paper, as is shown in Fig. 1, in which a space-variant lens array is used for performing log-polar mapping. The advantages of the proposed image sensor can be concluded as followings: 1) High speed. Rather than using space-variant pixels, the proposed retina-like image sensor uses space-variant lens array for log-polar mapping, thereby resulting in comparatively big space between two adjacent photodetectors in the corresponding space-invariant photodetectors array, as is shown in Fig. 1. 2) High sensitivity. In the proposed sensor, each photodetector is corresponding to a convergent lens; thereby each photodetector can receive more light energy than the photodetector of the previous retina-like image sensors. 3) Big planar array. Due to the fact that the proposed sensor uses conventional space-invariant photodetector array, the big planar array of retina-like image sensor can be achieved by increasing the amount of the space-variant lens as well as photodetectors.

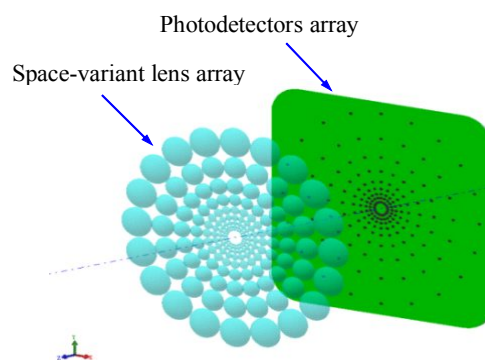


Fig. 1. The retina-like sensor based on space-variant lens array

2. MATHEMATICAL MODEL

2.1 System constructure

The retina-like imaging system is mainly composed of the front optical system, the non-uniform lens array, the non-uniform photodetectors array, the signal processing circuit, as is shown in Fig. 2. The

basic principle is: the non-uniform lens array of different diameter and focal length receipt the converging ray from the front optical system. The ray from the lens will be focused on the corresponding photodetectors, which photoelectrically converts the optical signal into the corresponding electrical signal; finally, the signal processing circuit deal with the electrical signal and make it as an output.

As shown in Fig. 1, the non-uniform lens array were arranged similar to the ring of polar coordinate, the diameter of the innermost one is the smallest, while the diameter becomes larger and the resolution becomes lower from the inside to the outside, which simulates the arrangement of human eye retinal photoreceptor cells. The non-uniform photodetectors locate behind the focus of its corresponding lens. The signal processing circuit is at the end of the system, from which the signal is read out according to a certain way.

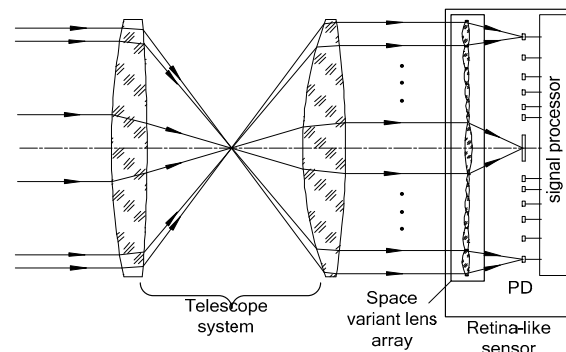


Fig. 2. The system structure of the retina-like image sensor based on space-variant lens array

2.2 Mathematical model of the lens array

The non-uniform lens array that have M rings and N lens in each ring is proposed, the lens diameter of different rings increases exponentially while the lens diameter of the same ring is equivalent, the lens of adjacent rings is tangent. In the Cartesian coordinate system, the N lens of each ring are located in the center of the circle of radius r_i , and the radius of the M rings increases exponentially. ($r_i = r_1 q^{i-1}$, where r_1 is the radius of the innermost ring, q is the growth factor between different rings, r_i is the radius of each ring).

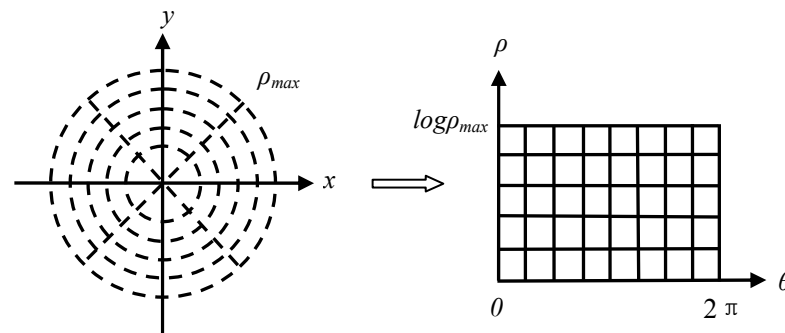


Fig. 3. The log-polar mapping

$$\begin{cases} \rho = \log_q \sqrt{x^2 + y^2} \\ \theta = \arctan(y/x) \\ q = \frac{1 + \sin(\pi/N)}{1 - \sin(\pi/N)} \end{cases} \quad (1)$$

The element with coordinate (x,y) in the Cartesian system will be mapped to the element with coordinate (ρ,θ) in the log-polar system through the retina-like imaging system, as is shown in Fig. 3. The coordinate (ρ,θ) in the log-polar system can be obtained by formula (1). The circular area in the Cartesian system will be converted into the rectangular area in the log-polar system. It can be concluded that the radial scaling and angle rotation in the Cartesian system will be changed into the shift of the horizontal and vertical direction.

The non-uniform lens array that has 5 rings and 36 lens of each ring have been designed in this system. The maximum radius of the system is $r_{max}=30$, as is shown in Fig. 4(a). It can be concluded that the radius of the blind hole in the middle is $r_0=12.5212$, the growth factor between rings is $q=1.1910$, the diameter of the lens of each ring is $D_1=2.3910$, $D_2=2.8475$, $D_3=3.3913$, $D_4=4.0389$, $D_5=4.8101$, the relationship between the radius r_i of the ring at which the center of the lens was located and the number of the rings is shown in Fig. 4(b).

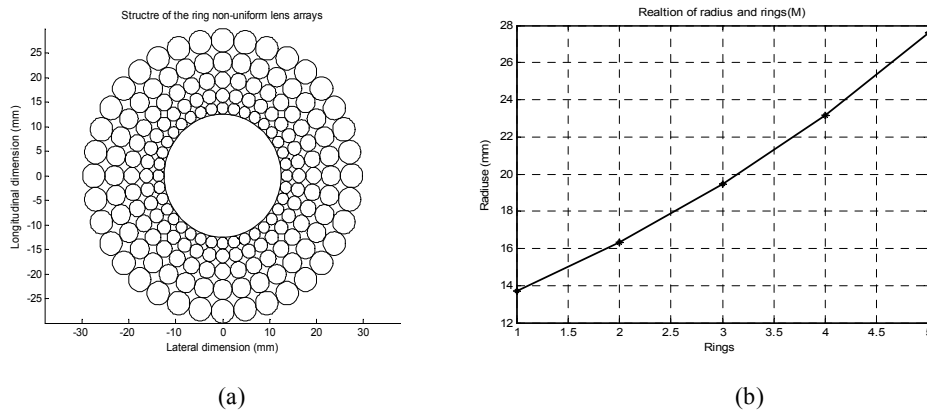


Fig. 4. The structure of non-uniform lens array

3. SYSTEM DESIGN

3.1 Hardware design

3.1.1 Circuit constructure

The hardware of retina-like imaging system is mainly composed of the photodetectors array, the photodetectors selection circuit, the consistent correction between different rings, the signal process circuit and the display module. Taking the operation speed and the number of interfaces that needed into account, the entire hardware system should be controlled by FPGA. The composition diagram is shown in Fig. 5.

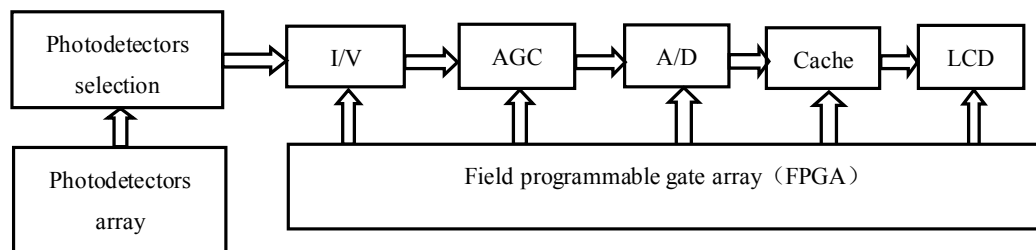


Fig. 5. The hardware structure of the retina-like imaging system

3.1.2 Photodetector array module

The photodetectors array in this system consists of the discrete components, so the photoelectric conversion device of each pixel must be selected suitably and distributed in the form of array. The phototransistor is selected in this system because it can convert the illumination to the current signal.

Since the photodetectors array has too many phototransistors, if all the transistors are in conduction while imaging, the signal processing system is too huge to be integrated and minimized. So considering the transistor to be time-division working, the MOS transistor is selected for conduction switch, because the change delay of drain voltage is ns level for the change of gate voltage. The voltage drop for the MOS transistor conduction is almost negligible because of the small drain-source resistance. At the same time, the maximum on-current is 1mA ,which result in the meet of the system while increasing the number of detectors. As is shown in Fig. 6, the drain of MOS is connected to voltage 2.85V and the gate of MOS is connected to control signal while the source of the MOS is connected to the collector of the transistor. There are 36 MOS transistors in this system, only one gate of the 36 MOS transistors is connected to the high level voltage at the same time, which controls the conduction of radial five transistors. A complete image is finished after the sequential 36 times conduction of radial transistors.

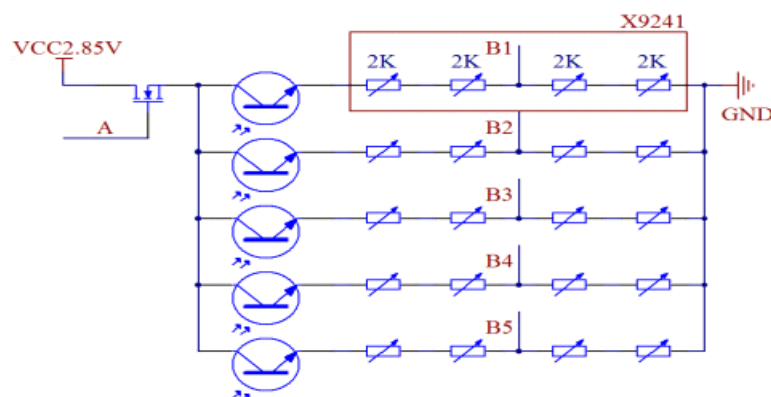


Fig. 6. The structure of the photodetectors

3.1.3 Signal processing and display module

Since the diameter of each lens in different rings is not same, the diameter of the outer ring is the maximum, under the condition of the same light intensity, the photodetectors in the outer ring obtain the most light intensity, the emitter currents of these phototransistors are also the largest, in contrast, the current of the inner ring is the minimum. Since the current from the photodetectors array is converted to the digital gray scale signal, if the system has no calibration sector, the array will obtain an image that is equal in same ring and differs in different rings when response to the same light intensity . Therefore, under the condition of same light intensity, in order to keep the character of gray scale while regardless of the position of the image pixel in the photodetectors array , the calibration sector must be carried out for the electric signal from the photodetectors array.

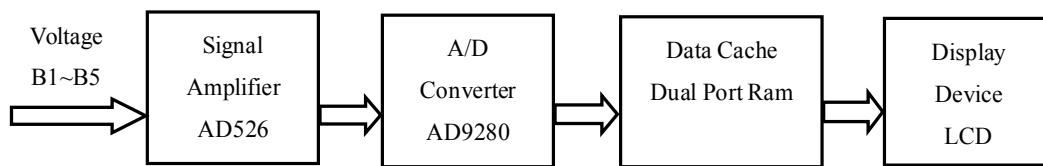


Fig. 7. Schematic of preprocessing circuit

For the photocurrent error in different rings, we regulate the load resistor in order to realize the current-voltage conversion, and accomplish the calibration sector. This system use X9241 nonvolatile digital potentiometer as the variable load to process the five voltage signal in parallel channel. As shown in Fig. 6, the X9241 integrate four maximum to 2kΩ, 64-bit step adjustable resistance on chip. Considering the rear amplification and input voltage range of the A/D converter, we select B1~B5 as the position of the output voltage, the maximum load resistance is 4kΩ, and the ratio N which equals the output voltage of true voltage is

$$N = \frac{N_1 + N_2}{N_1 + N_2 + N_3 + N_4} \quad (2)$$

Wherein N_1, N_2, N_3, N_4 is the step value between any number of 0 to 63 for the four resistance. This allows the five output voltage can be adjusted preciously for signal normalization. When taking the relative small light intensity into account , the photocurrent is relatively weak, the voltage from the load is not sufficiently converted into the linear range of the A/D conversion device. In order to meet the low-light imaging demand, this system uses the programmable amplifier AD526 to amplify the output voltage of B1~B5. The amplified voltage meets the needs of the A/D device and is converted into five 8-bit gray scale values to the display module, as is shown in Fig. 7. Taking the need of miniaturization for the system into account , a 320×240 pixel LCD is selected to display gray scale images, which meet the size and power requirements.

3.2 Software design

System programming uses FPGA as the core of the system to control every module, including the clock signal in every module from the PLL frequency divide; controlling the nonvolatile digital

potentiometer through the I²C bus; adjusting the programmable gain amplifier through controlling the pin level; controlling the gate level of MOS transistor to select every five phototransistors sequentially in radial direction; using RAM to cache 8-bit gray scale values of each pixel after A/D conversion and show the logarithmic polar coordinate mapping images on the LCD while generating horizontal sync, vertical sync signals. The simulation waveforms of this procession is shown in Fig. 8.

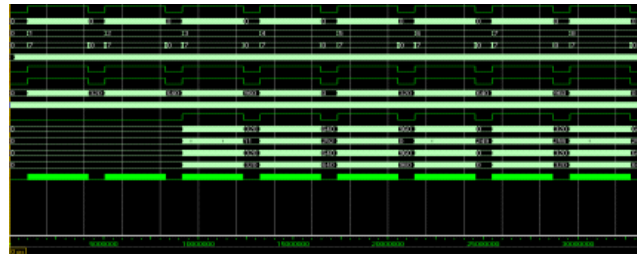


Fig. 8. The simulation waveform of the data cache

4. EXPERIMENTS

4.1 Experimental devices

Experiment is carried out under conditions of total darkness and equal intensity light from the parallel collimator. Fig.9 is a diagram of the experiment, the light source irradiates on the ground glass and parallel light is formed after the lens, which simulates the object imaging of the telescope system. The light goes through the target, imaging on the photodetector through the non-uniform lens array and the final image can be obtained via the signal processing circuit. The characteristic of rotation and scaling invariance property for this system can be validated by changing the rotation angle and scaling size of the target.

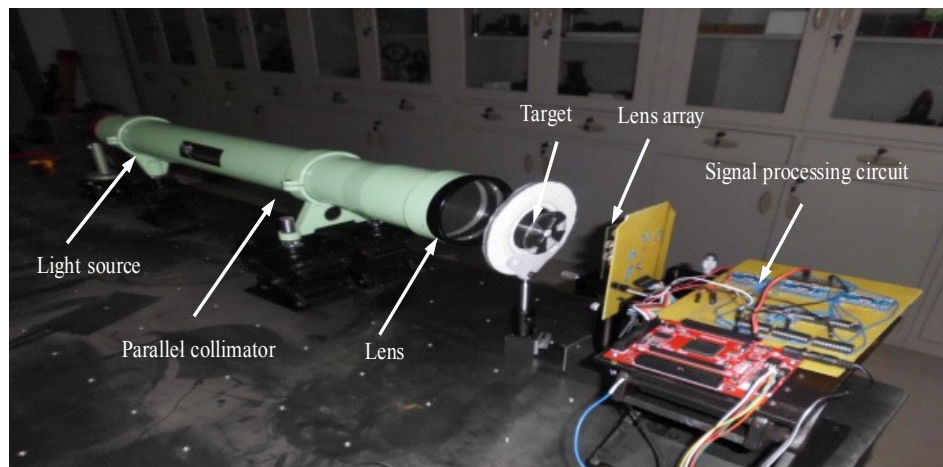


Fig. 9. The experimental facility

4.2 Experimental results

The function of the target in this experiment is to provide an image which has an apparent change of rotation and scaling. In order to verify the characteristic of scaling variation, the original and enlarged targets are shown in Fig. 10(a) and Fig. 10(c), their logarithmic polar coordinate mapping images are shown in Fig. 10(b) and Fig. 10(d), in which the horizontal direction is the angle axis, the vertical direction is the radius axis. It can be concluded that the scaling of the target in Cartesian system results in the target shift along the radius axis in log-polar mapping system. The original and clockwise rotation of 20° target are shown in Fig. 11(a) and Fig. 11(c), and their corresponding log-polar coordinate mapping images are shown in Fig. 11(b) and Fig. 11(d). It can be concluded that the rotation of the target in Cartesian system results in the target shift along the angle axis in log-polar mapping system. The experimental results show that the retina-like imaging system has a well identifying characteristics of rotation and scaling, which can be widely applied in the field of visual navigation and image processing.

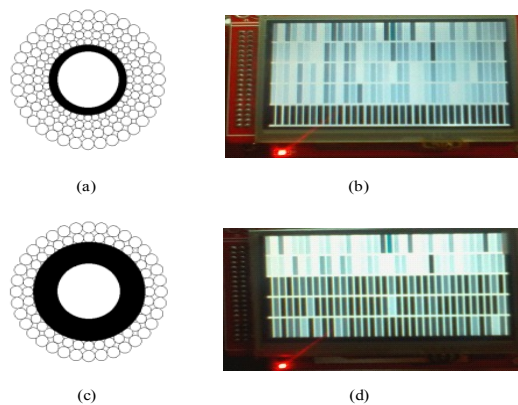


Fig. 10. The experimental results of target scaling invariance property

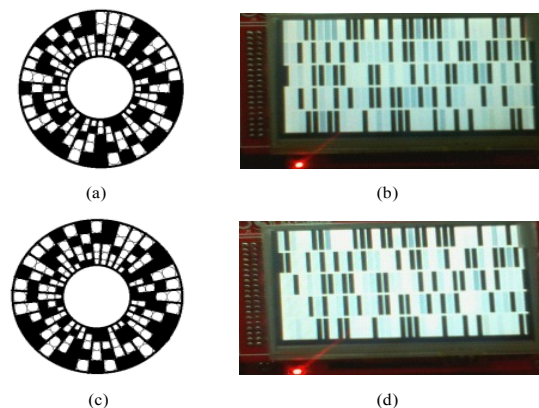


Fig. 11. The experimental results of target rotation invariance property

5. CONCLUSIONS

Compared with the conventional imaging sensor system, the developed retina-like imaging system using non-uniform array of photodetectors to obtain the non-uniform image of the object, retaining the high resolution of the interest region while ignoring the periphery feature, which reduces the amount of information of the image. Field programmable gate array (FPGA) is also used to control the selection of the photodetectors array, correct consistency between the rings, the display of the image and other functions, which results in improving the system speed, lowering the power consumption. The experimental results show that the system can run accurately and image well.

Acknowledgments

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