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An LED-based image sensor with energy harvesting and projection capabilities college of technology

Xiaozhe Fan
Purdue University

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Is approved by the final examining committee:

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James Christopher Foreman

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Approved by Major Professor(s): W Daniel Leon-Salas

Approved by: Kathryn Newton 7/27/2016
Head of the Departmental Graduate Program Date
AN LED-BASED IMAGE SENSOR
WITH ENERGY HARVESTING AND PROJECTION CAPABILITIES
COLLEGE OF TECHNOLOGY

A Thesis Proposal
Submitted to the Faculty
of
Purdue University
by
Xiaozhe Fan

In Partial Fulfillment of the
Requirements for the Degree
of
Master of Science

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West Lafayette, Indiana
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<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter</td>
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<td>APS</td>
<td>Active Pixel Sensor</td>
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<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
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<tr>
<td>DAC</td>
<td>Digital-to-Analog Converter</td>
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<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
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<tr>
<td>HID</td>
<td>High Intensity Discharge</td>
<td></td>
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<tr>
<td>IM</td>
<td>Intensity Modulation</td>
<td></td>
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<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
<td></td>
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<tr>
<td>LDO</td>
<td>Low-Dropout</td>
<td></td>
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<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
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<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
<td></td>
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<tr>
<td>PWM</td>
<td>Pulse-Width Modulation</td>
<td></td>
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<tr>
<td>SPS</td>
<td>Self-Powered Sensor</td>
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<tr>
<td>UART</td>
<td>Universal Asynchronous Receiver/Transmitter</td>
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<tr>
<td>VHDL</td>
<td>Very High-Speed Integrated Circuit Hardware Description Language</td>
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ABSTRACT

Fan, Xiaozhe M.S., Purdue University, August 2016. An LED-Based Image Sensor with Energy Harvesting and Projection Capabilities College of Technology. Major Professor: Walter D. Leon-Salas.

The light emitting diode (LED) technology has experienced great improvements in efficiency and cost reduction since the first visible light LED was invented in 1962. At the same time, because LEDs exhibit excellent photovoltaic performance, their capabilities of sensing light and harvesting energy have also been explored and studied for many years. By triple functionality of LEDs, they are widely used in a variety of research areas including visible light communication, robotics, structured light application and so on. Meanwhile, this triple functionality of LEDs also inspired researchers to combine and implement different functions in one system.

In this thesis, An LED-based image sensor with energy harvesting, image sensing, and projection capabilities was designed. A proof-of-concept prototype was fabricated and tested. The experimental setups, measurements and data analysis were carried out on the sensor prototype. The results shows the LED-based image sensor was able to work in three different functions. When the sensor works in the image sensing mode, clear images can be captured and easily be distinguished from the background. When the sensor works in the projecting mode, a linear amplification of optical images by 1.5 X and optical density of 28.9 $\mu$W/cm$^2$ were achieved on a white screen around 9 inches away from the prototype. In addition, the sensor can harvest 16.2 mW of power when all of LEDs are configured to harvest energy.
CHAPTER 1. INTRODUCTION

During the past decades, light-emitting diode (LED) technology has experienced unprecedented progress. The most notable progress in the LED technology has been the improvement of external efficiency, which can reach more than 50% now based on AlGanP compound semiconductors. The other remarkable advance in the LED technology is the coverage of whole visible spectrum. All of these improvements make LED to be irreplaceable light sources in the current market. The output light intensity of LEDs can reach higher luminous flux level than that of traditional light sources. Moreover, LEDs have an outstanding operational life time as long as 50000 h compared to that of incandescent sources (500 h) and fluorescent sources (5000 h), respectively (Schubert, Gessmann, & Kim, 2005).

There is no doubt that LEDs can be used as light emitters. However, the development of visible light communication (VLC) and semiconductor technology has triggered the emergence of using LEDs as light detectors. Based on the theory in solid-state physics, inorganic LEDs are p-n junctions, which open the possibility to treat LEDs as photodiodes. Although LEDs are mainly designed and fabricated for light emitting purpose, they are very effective when detecting light. This dual functionality which refers to light emission and detection has been underestimated by LEDs users for many years (Dietz, Yerazunis, & Leigh, 2003). Another major recent progress is the development of energy harvesting technologies which make it possible to extract the energy from environmental sources, especially for the sun. The state-of-the-art silicon solar cell can generate solar energy with efficiency up to 41.1% and make a great contribution to many applications. The LED, which is also a basic p-n junction, can produce energy from solar light for the miniature robotic system.
This thesis mainly focuses on LED-based image sensor with triple functionality of image sensing, energy harvesting and projection.

1.1 Scope

The LED-based image sensor with three distinct functions of image sensing, energy harvesting, and projection enlarge the scope of potential applications compared to that of modern CMOS image sensor. Every electronic product commonly used in daily life with screens such as cellphones, TVs, computers, PAD (tablet computers), etc. could gain benefits from additional functions of image sensing and energy harvesting. It is well known that the LED TVs and monitors gradually become competitive products in the electronic market and attract much more attention than LCD TV because of their higher resolution and extremely low power consumption. In addition, screens made by micro-LEDs are gradually becoming the future trend in which the display resolution can be further improved. By this future trend, displays fabricated by micro LEDs could be designed to incorporate three different functions including display, image sensing, and energy harvesting. The other application field that could take advantage of the triple functionality of LEDs is structured light imaging system in which a projector and a camera are used for lighting and imaging purposes, respectively. If the proposed LED-based image sensor in this thesis could replace the separately installed projector and camera, the size and cost of the system can be significantly reduced.

1.2 Significance

The primary significance of this thesis on an LED-based sensor comes from diverse and widespread potential applications. As mentioned in the previous section, applications vary from commercial products to scientific research. Some researchers are dedicated to exploring applications using LEDs as receivers (Dietz et al., 2003) (Komine & Nakagawa, 2004) (Haydaroglu & S, 2015). Some researchers
are making great efforts to test LEDs potential capability of harvesting energy
Moayeri and Leon-Salas (2015). The experimental results indicate LED panels could
generate enough solar energy for the self-powering miniature system. Others are
striving to fabricate LED-based projecting systems by combining flip-chip
technology and CMOS technology, which further reduces the whole size of the LED
panels as well as increases the light density (Lee & Kymissis, 2010). If it is possible
to combine these three different functions in the same system by modifying the
control circuitry without changing fabrication process of the LED, the usability of
the LED-based panel can be greatly increased.

1.3 Research Question

The central question to this study are listed below:

- How much power density can be achieved on the screen when the sensor works
  in the projection mode?

- How to operate a LED-based sensor in the image sensing mode and projecting
  mode at the same time?

- How much solar energy can be harvested with the proposed LED-based image
  sensor in an outdoor scenario?

- Given known experimental setup in the imaging mode, how much resolution of
  images can be achieved?

1.4 Assumptions

The assumptions intrinsic in this design are listed below:

- The power supply used for powering up the sensor is stable during the test.

- The methodology and design for this study are sufficient to answer the
  research questions.
• The LED-based sensor is powered by the power supply and is not relied on the power generated in the energy harvesting mode.

• The measurement devices in any experimental setup are precise enough.

• Discrete components designed in the system will work normally during the test circle.

• Commercially available off-the-shelf LEDs will be used.

1.5 Limitations

The limitations inherent in this design are listed below:

• The LEDs chosen for this design have been optimized in emitting light but not necessary for absorbing light.

• The accuracy of data collected during the experimental test depends on the accuracy of measurement tools in the lab.

• The coupling effect of digital signals on analog signals is inevitable in the design.

• The noise coupled from the external environment cannot be avoided.

• The real parameters and properties of electronic components are slightly different from that listed in the datasheets.

1.6 Delimitations

The delimitations inherent in this design are listed below:

• This system does not use battery to power itself.

• This system does not use the generated power to drive itself.
• This study does not focus on the problems in optical system.

• This study does not focus on the digital image processing part.

1.7 Definitions
This study mainly focuses on the LED-based sensor. Some brief definitions related to the image sensor and LED are listed below:

• Fill factor: is the ratio of photo-sensing area to the whole area in pixel

• Internal quantum efficiency: is the ratio of photons generated from active region per unit time to electrons passing to LED per unit time.

• Extraction efficiency: is the ratio of photons emitted into air per unit time to photons generated from the active region.

• Color Temperature: is the temperature of a Planckian black-body radiator which describes the comparable color hue of a white light source.

• Pixel resolution: refers to the number of pixels counted in image sensor. It also means the smallest details of objects can be observed.

1.8 Summary
This chapter introduces the background related to the research, deriving the essential research question. It details the scope and significance of the research and the contributions to the field. It also uneartths limitations the study may suffer from.
CHAPTER 2. REVIEW OF RELEVANT LITERATURE

During the past decades, light-emitting diode (LED) technology has experienced an incredible development. Since the first visible LED illuminated in the red spectrum was invented in the early 1960's, the LED technology gradually became a competitive product in the market, which owes to its vast improvements in efficiency, low power consumption and cost reduction (Bueno, Alonso, Munoz, & Marty, 2014). Also, its capability of generating light has gained enormously improvement because of graduate increase in the external efficiency. For now, the external efficiency of the state-of-the-art LEDs is more than 50% for ALGaInP semiconductor materials. Although the LED is mainly designed for lighting purpose, it also displays excellent photovoltaic performance which opens the possibility of using the LED in a large variety of applications beyond lighting, such as visible light communication (Komine & Nakagawa, 2004), projection (Kuhn, Groetsch, Breidenassel, Schnabel, & Wallner, 2005), and optically powered micro-systems (Haydaroglu & S, 2015). Meanwhile, widespread potential application range has further propelled researchers to explore the feasibility of implementing multiple functionalities of LEDs in one system.

Because of the LED semiconducting nature, it behaves as a p-n junction and performs three different functions including sensing, harvesting, and emission of light. It is no doubt that the LED is particularly good at emitting light because its fabrication process has been focused on improvement of light emission. According to the experiment results presented by Acharya (2005), the LED is also effective in detecting light with a specific wavelength range. Also, a better photovoltaic performance of the state-of-the-art LED with a power efficiency of 22% has been reported compared to that of photodiodes (Haydaroglu & S, 2015). The rest of
chapter is organized by reviewing relevant literature in LED applications when the LED works in different functionality.

2.1 Using an LED as a light sensor

When an LED is reversely biased by a moderate voltage, its internal capacitance will get charged. At the same time, if a light beam is shining on the LED, the capacitance will get discharged and generate a photocurrent which is proportional to the light intensity. This property associated with the LED is widely used in the LED-LED visible light communication, where LEDs behave as both of transmitters and receivers and photometers in which LEDs act as light detectors.

Dietz et al. (2003) presented a simple LED-to-LED communication interface circuit based on a microprocessor. In this work, the circuit can work in two different modes depending on the role of the LED either as a transmitter or a receiver. When the LED is forwardly biased, it works to generate light. The light intensity highly depends on the current flow across the LED. A serially connected resistor is designed in the system to limit the current flow through the LED and make the microprocessor work properly. When the LED is reversely biased, its capacitance gets charged and prepares the LED to receive optical information. By the time the light reaches on the receiver, the LED capacitance starts to be discharged by the photocurrent which is proportional to the light intensity. On one hand, if the LED does not receive light in the reception mode, the voltage at its anode will be kept high and perceived by the microprocessor as bit 1. On the other hand, if the LED receives light, the voltage at its anode will be lowered down by a discharging process and perceived by the microprocessor as bit 0. The main drawback in this work is low data transmission rate which is limited by discharging time. Because the discharging process is roughly linear, the time for discharging is proportional to the photocurrent and light intensity. Therefore, the transmission speed can be significantly improved using the LED with high illumination and photovoltaic
performance. A similar design was described in (Giustiniano, Tippenhauer, & Mangold, 2012). The only difference is the appearance of the resistor which has the effect on the charging speed of the LED. The transmission speed of this work gets visible improvement compared to that of (Dietz et al., 2003). But it still can be further increased using the LED with high luminous intensity and photovoltaic performance. To sum up, LED with excellent luminous intensity is suitable for lighting and projecting purpose while the one with the high photovoltaic performance at specific wavelengths is a good candidate for sensing.

Another research area, where LEDs are widely used as light sensors, is photometer. The photometry, which is conventionally made of an interference filter and a photodiode, converts the light signal to electric signal Acharya (2005). The photometer generates absorbance readings which are proportional to the photocurrent generated by the photodiode. Therefore, an amplifier circuitry is usually adopted to amplify the photocurrent and read out the corresponding light intensity at particular wavelength Hauser and Chiang (1993). Because the LED only responses to a narrow range of spectrum and generates photocurrents proportional to the light intensity, it can be used as a light filter and light detector at the same time. The current amplifier utilized in the LED-based photometer is similar to that in the photodiode-based counterpart.

2.2 Using an LED as a energy harvester

When an LED is forwardly biased by a small amount of voltage, it can be used as an energy harvester. The capability of harvesting energy is closely related to the LED photovoltaic performance. Haydaroglu and S (2015) presented a microsystem in which the data transmission and energy harvesting are implemented on the same LED. In this work, the selected LED exhibits better photovoltaic performance with a power efficiency of 22% even than the PIN photodiode. The energy harvested by the LED is stored in a big capacitor which is treated as a battery. When the
capacitor gets fully charged, the LED will then be forwardly biased. The whole process is automatically executed, and the data rate is highly dependent on the timing for charging the capacitor to the desired voltage level. Because of the low efficiency associated with the charge pump, the capacitor is only able to be charged to the desired level by a laser with high power density which is not allowed to use in the daily life. The author presented a possible solution in which the charge pump is removed from the system. But the voltage used to drive other components may not be leveled up to desired value. The possible solution should be using an LED array to generate power instead. A powering micro system with single LED still limited by the insufficient power generation. Moayeri and Leon-Salas (2015) described the way to harvest power with a LED array. In this work, the author evaluated LEDs with different colors and brands. According to the experimental results, the selected red LED can generate maximum 133 μW of among others. Also, the corresponding calculation was done with 96x216 LED array and result showed maximum 2.76 W of power could be generated which is enough to power up a microsystem.

2.3 Using an LED array as a projector

Light-emitting-diodes (LEDs) are mainly optimized for illumination purpose. With the development of LED technology and semiconductor materials, the brightness and efficiency of LEDs are significantly improved during the past decades, which also opens the possibility to output light with high power density when LEDs are addressed in a passive array. In this scenario, the LED array can be used as a projection source. The traditional projection system consists of a spatial light modulator (SLM), a lighted lamp, and a convex lens. The spatial light modulator is used to modulate the intensity of light and address the light beams into a particular pattern. However, the SLM will absorb a portion of light coming from the projection source and reduce the entire efficiency. As a result, optical power reach on the screen will be significantly reduced. However, with the advances
in LED luminous intensity and efficiency, the use of high-power LEDs as the projection source becomes possible (Lee & Kymissis, 2010). The LED-based projection source only consists of a passive LED array and a lens system, which significantly increase the overall system efficiency and reduces the power consumption by removing the SLM. Riehemann et al. (2009) presented a projection system with a microOLED-based array. The OLED-based projection source embraces several advantages including high brightness, low power consumption, high efficiency and so on. However, because the emission efficiency of the OLED is lower than that of the inorganic LED, the projection source made by an array of inorganic LED can achieve higher brightness for display. Lee and Kymissis (2010) fabricated a projection source with 10x10 addressed microLED array. The brightness of 100,000 cd/m² on screen has been reported, which is bright enough to project images. However, the light in this LED configuration is limited by the loading effect because of the fixed current flows in each column. Besides, the LED array can only be able to implement lighting purpose due to the circuit design. To achieve the full-color display, Liu, Chong, Wong, and Tam (2013) designed an innovative full-color microLED-based projector. According to this work, the projector can produce full-color image display by superposing light from three individual microLED panels through a trichroc prism. The main drawback associated with this is non-guided light path which results in nonuniform images projected on the screen.

2.4 Summary

This chapter has presented an overview of literature related to three primary applications of the LED based on the semiconductor theory. All of these research have gained significant progress during the past decades and opened the possibility to combine and implement those three functions together in the same system. Moreover, research in these three entirely different research areas combines to build a reasonable case for the research question.
CHAPTER 3. FRAMEWORK AND METHODOLOGY

This chapter specifies the framework and methodology used in designing the proposed LED-based image sensor. To validate the feasibility of this work, the image sensor, which is made of a 20x20 LED array and its supporting circuitry, has been designed with discrete components. As it is shown in Figure 3.1, the LED-based image sensor consists of a 20x20 LED array, a photocurrent amplifier, a DC/DC step-up converter with power management, a row-level switching block, a column-level switching block, a MOSFET-based switching block, a MUX-based switching block and a field programmable gate array (FPGA) for control and communication.

3.1 Hybrid LED-based pixel

The proposed LED image sensor consists of 400 inorganic LED-based pixels which are arranged in a 20x20 matrix. Light can be generated by each pixel through electroluminescence phenomenon in which photons are generated by recombination of electrons from n-type materials and holes from p-type materials. Furthermore, not only can light be produced by the radiative recombination of electrons and holes under forward-bias polarization but also be absorbed through the photovoltaic mechanism in which photons are converted to electron-hole pairs. This bi-directional behavior of LEDs can be further interpreted by observing current-vs-voltage (I-V) curve in Figure 3.2. The reverse-bias region, located at the most left side of the y-axis, is the area where LEDs are biased to sense light. No photocurrent is generated without illumination. However even in dark condition, a small amount of electric current, called dark current, still unavoidably flows across LEDs. The dark current is due to the thermally-generated charger.
When the incident light shines LEDs, the photocurrent, which is nearly proportional to the light intensity, is generated. In such condition, LEDs behave like light sensors. The photovoltaic region, where energy conversion from light to electricity occurs, is formed in the middle of the I-V curve. In this region, the product of photocurrents generated by LEDs and voltages applied to them is negative, which proves the behavior of LEDs as energy sources. As forward-bias voltages applied to LEDs further increase, the I-V curve enters the forward-bias region in which typical operation of LEDs as light sources is implemented. Therefore, depending on its polarization, an LED can work in three different functional modes including light sensing mode, energy harvesting mode and light emitting mode.
3.2 Design of the LED-based pixel array

In this work, a passive LED-based matrix, in which anodes arranged in the same row and cathodes arranged in the same column are connected, is implemented. In such configuration, a specified LED can be easily chosen and configured by enabling the corresponding row and column and being biased in different polarization. Two requirements should be considered during the design process. First of all, the LED-based array needs to be compactly designed to save space for incorporating more LEDs. Moreover, LEDs chosen for this application should be strongly sensitive to the incident light with particular wavelength while keeping their sensing area small. To sum up, the LED with small sensing area but with high photoelectric conversion efficiency are an ideal option for this design. However, the careful tradeoff has to be made between these two significant parameters based on structures of available LEDs, which means highly compacted pixel array with a large number of LEDs can only be implemented by decreasing light-absorbing area on each LED.
3.3 Design of the proposed image sensor

Figure 3.1 shows the schematic design of the proposed sensor system with discrete components. The proposed LED image sensor is made of seven main functional blocks: an adjustable low dropout regulator (LDO), a DC/DC boost converter with power management, a photocurrent amplifier, row-level switches, column-level switches, a bank of MOSFET transistors and a bank of 4:1 multiplexers. More details are developed to describe those functional blocks in the rest of section.

3.3.1 Design of the adjustable LDO block

The adjustable LDO, made of a fixed LDO and its external voltage-regulating resistors, is designed to meet the opposing requirements of high-current operation in the projecting mode and low power consumption in both of the sensing mode and energy harvesting mode. It is worth noting that three basic criteria should be satisfied in selecting desired LDO. First of all, according to the initial design consideration to the power distribution in the projecting mode, the maximum current in each LED column is not allowed to exceed 25mA to achieve a tradeoff between a high quality projection and moderate power consumption. Therefore, the total current in the sensor will be less than 500mA even if all of the LEDs in the same column are enabled in the projecting mode. Moreover, the power dissipated by the adjustable LDO needs to be kept extremely low when it is not being used in the energy harvesting mode. The last but not least, the voltage-regulating resistors built around the fixed LDO should be kept as large as possible to reduce the overall power consumption in the image sensing mode. In such condition, the total power consumed by the adjustable LDO can be calculated by:

\[ P_{total} = \frac{V_{LDO}^2}{R_4 + R_5} + P_{chip} \]  \hspace{1cm} (3.1)

where \( V_{LDO} \) is the voltage output of the adjustable LDO, \( R_4 \) and \( R_5 \) are the serially connected voltage-regulating resistors with which voltage outputs can be controlled.
and adjusted. $P_{chip}$ is the power dissipated by the fixed LDO. The overall power consumed by the adjustable LDO can be significantly reduced as values of the resistors increases. When the pixel array works in the projection mode, the adjustable LDO is configured to output 1.8V, which is adequate to turn on LEDs in the pixel array. In this mode, only one row of LEDs can be enabled at once, and the others are disabled by leaving their anodes floating. Figure 3.3 shows the I-V characteristic curves of the pixel array with a different number of lighted LEDs in the projecting mode. It can be observed that more current will be generated by the adjustable LDO as the number of glowing LEDs in a row increases. Given a certain value of the voltage output in the adjustable LDO, the maximum current flow in the pixel array can be achieved by turning on all of the LEDs in a row at the same time. In the real design, roughly 194mA current at most can be generated by the adjustable LDO, given its the output voltage 1.8V. In the sensing mode, the adjustable LDO is configured to output a voltage level which is small enough to keep the LED in the reverse-bias condition. In the energy harvesting mode, the adjustable LDO is disabled when the fixed LDO enters the shutdown mode.

3.3.2 Design of four switching blocks

To work in different functions including energy harvesting, image sensing and projection, the LED-based sensor is configured by operating four different switching blocks including the row-level switching block, the column-level switching block, the bank of MOSFET transistors and the bank of 4:1 multiplexers. The row-level switching block consists of twenty 3:1 multiplexers through which the LED anodes in a row are able to be either connected to the output of the adjustable LDO and the DC/DC converter respectively or kept floating. The column-level switching block is made of twenty single-pole, double throw (SPDT) switches through which the LED cathodes in a column are able to be linked to ground or the photo-current amplifier. The bank of MOSFET transistors determines the on or off states of LEDs
Figure 3.3. The I-V characteristic curves of the pixel array with different number of lighted LEDs in the projecting mode.

in a column by applying two different voltage levels (3.3V or 0V) to the MOSFET gates. The bank of 4:1 multiplexers is used to enable the connection between LED cathodes in a column and the photocurrent amplifier in the image sensing mode. When the LED-based image sensor works in the projection mode, the forward voltage of the LED specified in the datasheet brings the voltage at the LED cathode down to a level which is low enough to drive the serially connected MOSFET transistor (Panasonic FC6932010R) in triode region and operate it as a switch. Figure 3.3 shows the current-vs-voltage curve of the selected transistor with 3.3 V gate-to-source ($V_{GS}$) voltage. The MOSFET transistor in the design will work in the triode region as long as its drain-to-source voltage is lower than 500mV. A simple circuit has been built to measure the voltage at the MOSFET drain terminal as shown in Figure 3.5. A source-meter (model: ADALM1000) was used to perform the test. In this circuit, an LED (LUMILED LXZ1-PH01) is serially connected to the MOSFET transistor. The measurement is done by applying a swing voltage
\((V_{\text{swing}})\) from 0 V to 2.5 V at the LED anode and a fixed voltage 3.3 V \((V_G)\) at the MOSFET gate, and measuring the corresponding voltage \((V_D)\) at the MOSFET drain. Given 1.8 V voltage at the LED anodes in the projecting mode, the voltage measured at the MOSFET drain terminal is roughly 40mA, which is much lower than 500mV. In this case, the MOSFET transistor will even work in the deep triode region. The on-resistance of the MOSFET transistor can be roughly determined by (Razavi, 2000):

\[
R_{\text{on}} = \frac{1}{\mu_n C_{\text{ox}} \frac{W}{L} (V_{GS} - V_{TH})}
\]  

(3.2)

Where \(\mu_n\) is the mobility of electrons, \(C_{\text{ox}}\) is the gate oxide capacitance per unit area, \(W\) and \(L\) are the width and effective length of the MOSFET gate respectively and \(V_{TH}\) is the threshold voltage. The values of \(\mu_n, C_{\text{ox}}\) and the ratio of \(W\) and \(L\) are fixed on the known transistor. Therefore, the on-resistance of the transistor is the linear function of the "overdrive voltage", \(V_{GS} - V_{TH}\). In our design, \(V_{GS}\) is 3.3 V and \(V_{TH}\) is varying around 1V, A pulse width modulated (PWM) signal can be applied to the gates of the transistors to control the brightness of the LEDs.

3.3.3 Design of the photo-current amplifier

When reversely biasing an LED with a moderate voltage, the photo-current, nearly proportional to the incident light, is generated. However, the photo-current is too small to be directly detected by most of electronic measurement tools. Therefore, building photo-current amplifier to amplify the photo-current becomes a significant step. In the presented system, the photo-current amplifier contains two serially connected amplifiers, a trans-impedance amplifier A1 and a differential amplifier A2. A digital-to-analog converter (DAC) sets the bias voltage by applying reference voltage \(V_{REF}\) at the positive terminal of opamp A1 (see Figure 3.1). By virtue of the high gain and negative feedback of A1, the LED are reversely biased
by $V_{REF} - V_{LDO}$ as long as $V_{REF} > V_{LDO}$ in the sensing mode. From the schematic diagram in Figure 3.1 the output of A1 is given by (Mark & Michiel, 2004):

$$V_{O1} = V_{REF} + R_1 I_{ph}$$

(3.3)

where, $I_{ph}$ is the LED photocurrent. It can be clearly seen from equation above that $V_{O1}$ suffers from a limited signal swing from $V_{REF}$ to $V_{DD}$, where $V_{DD}$ is the supply voltage of A1. To improve the signal swing so that the full input range of the ADC is used, the differential amplifier, constructed by A2 and resistors $R_2$ and $R_3$, is employed. The output of the differential amplifier is given by:

$$V_{O2} = \frac{R_3}{R_2} (R_1 I_{ph})$$

(3.4)

Considering the resistor values used in the design ($R_1=100 \, \text{K}\Omega$, $R_2=10 \, \text{K}\Omega$, $R_3=1 \, \text{M}\Omega$) yields an overall trans-conductance of $10^7 \, \Omega$. Given a 12-bit ADC and $V_{DD}$ used in the design, the maximum photocurrent that can be measured is 330 nA from Equation 3.4.
The FPGA generates control signals for the row-level and column-level switching blocks, the multiplexers and the MOSFET gates. At the same time, the FPGA is also used to program the DAC and the potentiometer, read the ADC output and transmit the acquired images serially to a PC where they are displayed. The DC/DC step-up converter is used in the energy harvesting mode to charge a super-capacitor with the photo-current generated by the LEDs.

3.4 Operation of the proposed sensor

By the proposed LED-based image sensor, four essential functions can be implemented by the system including energy harvesting, image sensing, projection and a combination of image sensing and projection. In the projection modes in Figure 3.5, rows are sequentially enabled by connecting LED anodes in a row to 1.8 V output of the LDO, which is enough to turn on LEDs in the sensor, via the row-level switches. All of columns are enabled by connecting LED cathodes in a
column to the corresponding MOSFET transistor. The MOSFET transistors, used as switches, are then turned on or off according to images to be projected. In the sensing mode in Figure 3.6, the LED array is addressed in a raster scan fashion. Rows are sequentially enabled by connecting LED anodes in a row to 1.24 V output of the LDO via the row-level switches. Columns are then sequentially enabled by connecting LED cathodes in a column to the current amplifier, which applies voltage higher than 1.24 V to the cathode of the selected LED, via column-level switches and multiplexers. In this case, the selected LED is reversely biased and corresponding photocurrent is generated and read out by the current amplifier. When the sensor works in the energy harvesting mode in Figure 3.7, all of rows are enabled by connecting LED anodes in a row to the input of the DC/DC converter.
Figure 3.7. The schematic of proposed sensor in the imaging mode. (Note: components in gray are disabled in this mode).

and all of columns are enabled by connecting LED cathodes in a column to the ground. By this functionality, the entire sensor works to harvest energy. By combination of operations in the sensing mode and projection mode, the sensor can work to sense and project images at the same time as can be seen in Figure 3.8. The column-level MOSFETs are turned on or off according to images being projected. In Figure 3.7, All of the LEDs are turned on when addressing the first row. A pulse width modulated (PWM) signal can be applied to the gates of the transistors to control the brightness of displayed images. When the sensor works in the image sensing mode, the LED cathodes in the enabled row are then sequentially connected to the current amplifier via the MUX-based switch block which is made of five multiplexers MUX1 to MUX5. At the same time, all of the columns are
enabled by connecting the LED cathodes in columns to the MUX-based switching block via the column-level switches as shown in Figure 3.7. In such scenario, optical information can be read out from one pixel to another and then converted to digital information by the ADC. The whole sensor array can be used to harvest energy when it is operated neither in the image sensing mode or the projection mode.

When working in the energy harvesting mode, all of the LED cathodes are connected to ground via the column-level switching block and the MOSFET-based switching block while the LED anodes are connected to the DC/DC converter input via the row-level switching block as shown in the Figure 3.8.
3.5 Summary

This chapter provided the framework and methodology required to design an LED-based sensor with the triple functionality of energy harvesting, image sensing and projecting. The sensor and its supporting circuitry were discussed in this chapter. Additionally, it contains all associated values needed to be extracted from the sensor and to be analyzed by the software.
CHAPTER 4. RESULTS

Based on the methodology described in Chapter 3, a proof-of-concept LED-based image sensor has been fabricated. The sensor, built on a printed circuit board (PCB), was outfitted with a lens (Anchor Optics double-convex lens with 63 mm diameter and 48 mm focal length) and enclosed in a custom 3D-printed case as shown in Figure 4.1.

Three different experimental setups have been built to test and validate the proposed design. In these settings, the sensor was configured to work in the energy harvesting mode, image sensing mode and projection mode respectively. When the sensor worked in the energy harvesting mode, the current-vs-voltage (I-V) characteristic curves of the pixel array were measured in an outdoor scenario. In the I-V curves, the power harvested by the sensor can be calculated from each voltage point by:

\[ P_D = V_D I_D \]  \hspace{1cm} (4.1)

where \( V_D \) is the voltage applied to the sensor and \( I_D \) is the photocurrent generated by the sensor. And then corresponding power-vs-voltage (P-V) characteristic curves can be derived. By plotting and analyzing the P-V characteristic curves, the total power harvested by the pixel array was measured, and photovoltaic performance of the LED was evaluated. When the sensor worked in the image sensing mode, its capability of sensing and capturing images was tested and analyzed. When the sensor worked in the projecting setup, the feasibility of operating it to project images on targeted screen was testified.

In section 4.1, the photovoltaic performance of the selected LED are evaluated. In section 4.2, the fabrication process of the pixel array is described in detail. In section 4.3, we illustrate discrete components mounted on the PCB. In section
Figure 4.1. Built proof-of-concept prototype of the LED-based image sensor. a) the pixel array with mounted lens and b) the assembled prototype

4.4, 4.5 and 4.6, the experimental setups, measurements, and results are presented when the sensor works in the energy harvesting mode, image sensing mode and projection mode respectively. Section 4.7 reveals the limitations and future works. In section 4.8, the whole work is summarized and concluded.

4.1 Selection and evaluation of LED-based pixel

In the LED-based sensor, each LED acts as a basic pixel unit in which triple functionality of energy harvesting, image sensing and image projection can be achieved. When the sensor works in the image projection mode, the more light it generates, the brighter images can be projected on the targeted screen. Therefore, high brightness is one of criteria in the LED selection process. Also, when the sensor works in the image sensing mode, the resolution of images can be improved
as the number of pixels increases given the fixed sensor size. In other words, if the number of pixels is fixed, the sensor is expected to be as small as possible, which can be only achieved by choosing LEDs with smaller size and keeping the LED array more compact. In this work, the bare-die LED (OSRAM OD-A20RF) was selected as our initial choice because of its small size and high brightness (Appendix Chapter1). Although the size and brightness of the LED can be seen from the datasheet provided by the manufacturer, the photovoltaic performance which interpreting the LED capabilities of harvesting energy and sensing light can only be tested using the experimental setup for current-vs-voltage (I-V) characteristic curve measurement. The I-V curve is proven to be the most straight-forward way to learn the LED photovoltaic performance. Figure 4.2 shows the experimental setup for measuring the LED photovoltaic performance in our work. The setup contains a light generator (Thorlabs OSL2), several optical filters, a beamsplitter, a optical power sensor (Thorlabs S120C), a source meter (keithley 2401) and a PCB on which a targeted LED mounted. The optical power sensor and the PCB are placed at the same distance away from the beamsplitter. Therefore, the optical power received by
the sensor is equal to that by the PCB. In this experimental setup, a uniform light beam is constantly generated by the light generator in with calibration functionality is included. After passing though the optical filter, the light beam forms a 132.6 mm² luminous area in a circular pattern on both of the sensor and the PCB as illustrated in Figure 4.2. By reading out optical power from the sensor, the total power received by the LED can be then obtained. The source meter is used to measure the LED I-V characteristic curve by biasing the LED with a range of voltages and reading out corresponding currents. After measuring the I-V characteristic curve, the corresponding P-V curve can be derived and maximum power harvested by the LED can be estimated. The I-V characteristic curve of the OD-A20RF LED was measured using the experimental setup shown in Figure 4.3. As observed from the I-V curve in Figure 4.3, the OD-A20RF LED was the most sensitive to 600 nm wavelength in which the best photovoltaic performance could be nearly achieved. In the experiment, the 600 nm uniform light with optical power density 82.8 nW/mm² reached on the PCB surface. The total power received by the LED with 0.5 mm x 0.5 mm dimension was 20.7 nW. In this case, the maximum power of 17.5 nW could be harvested when the LED worked in the maximum power point (MPP) and therefore 84.7% conversion efficiency could be achieved. The LED (Lumileds LXZ1-PH01) with package were selected as our backup choice. Frequent movement of the sensor system and adjustment of the lens tube introduce vibration to the LED mounted on the PCB. The LXZ1-PH01 LED is robust enough to this type of vibration. The I-V characteristic curve of the LXZ1-PH01 LED was measured using the same experimental setup as shown in Figure 4.4. The LXZ1-PH01 was also had the highest response to 600 nm wavelength. In the experiment, the 600 nm uniform light optical power density 80.6 nW/mm² reached on the PCB surface. The total power received by the LED with 1 mm x 1 mm die dimension was 80.6 nW. The picture of the packaged LED can be seen from Figure 4.5. According to the measurement result, the maximum power of 67.9 nW could be
harvested when the LED worked in the MPP and 84.2% conversion efficiency could be achieved.

Figure 4.3. I-V curve and P-V curve of the OD-A20RF LED. a) the array with OD-A20RF LED and b) the array with LXZ1-PH01 LED
Figure 4.4. I-V curve and P-V curve of the LXZ1-PH01 LED. a) the array with OD-A20RF LED and b) the array with LXZ1-PH01 LED

4.2 Pixel Array Fabrication Process

The 20x20 pixel array, mounted on the PCB board, has two different versions as shown in Figure 4.6. The left picture shows the PCB board fabricated with the
Figure 4.5. The OD-A20RF LED with 0.5 mm x 0.5 mm effective absorption area and the LXZ1-PH01 LED with 1 mm x 1 mm effective absorption area.

Figure 4.6. The fabricated 20x20 LED-based pixel array. a) the array with OD-A20RF LED and b) the array with LXZ1-PH01 LED.
Figure 4.7. The 20x20 pixel array layout on the PCB with different amplification. a) 0X; b) 30X and c) 200X

Figure 4.8. The experimental setup for die bonding process

OD-A20RF LED, and the picture on right shows the PCB board built with the LXZ1-PH01 LED. The rest of section is developed to specified two different procedures through which two different pixel arrays were fabricated.

4.2.1 Pixel Array Fabrication with OD-A20RF LED

The process used for fabricating the pixel array with OD-A20RF LED is similar to that of chip-on-board (COB) technology, which describes mounting a bare-die
LED on the substrate to achieve higher packing density (Jinka et al., 2007). In our case, we mounted LED dies on the PCB to create a compact LED array. Three basic steps have been employed in the whole array fabrication including PCB layout design, die bond and wire bond.

4.2.1.1. PCB layout design

This section describes the PCB layout for 20x20 LED-based pixel array. The OD-A20RF LED, as the basic pixel, has 0.5 mm x 0.5mm square-based p-type contact and circle-based n-type contact with 0.2mm diameter (OSRAM, 2009). To arrange LEDs in a 20x20 matric pattern, the PCB layout with 0.8 mm x 0.8 mm pad and 0.2 mm x 0.2 mm pad, were designed using PCB Artist (Appendix Figure B.1). Figure 4.7 shows pictures of the fabricated board with different amplifications. In this context, 0.8 mm x 0.8 mm pads are called big pad while 0.2 mm x 0.2 mm pads are called small pad. In the PCB, the big pads were designed to hold LEDs and connected to the LED p-type contacts. The small pads were connected to the LED
n-type contacts by wire bonding technique. The whole pixel array can be accessed and controlled through two 20-position connectors located on the back of PCB.

This section describes necessary materials and devices used in the die bonding process as well as details several indispensable steps needed for mounting LED dies on the PCB. Figure 4.8 shows the experimental setup for die bonding. The purpose of this working portion is achieve a good electrical connection and precise matching between the LED p-type contacts and the PCB big pads. The electric medium used for connection is electrically conductive epoxy (Atom Adhesives AA-DUCT 902) instead of solder. Electrically conductive epoxy is proved to be the best choice through which two targeted objects with the same dimensions can be easily connected. In addition, the low-temperature healing process of the conductive
Figure 4.11. LEDs with bonded wire

epoxy brings no damage to selected LEDs. The conductive epoxy used in our design is AA-DUCT 902 with the electrical resistivity less than 0.0001Ωcm (Atom Adhesives, 2016). The dispensing device (Mikros Fluid Dispensing Pen) ensures tiny drops of epoxy adhesive to be precisely deposited at the center of the big pads. The basic rule for successful dispensing process is to create epoxy adhesive drop which occupies half of the big pads. This is to guarantee the epoxy not being scattered out of the pad when attaching the LED die on the PCB. The device used for stabilizing the LED is the vacuum tip which generate enough attractive force to suck the LED up and keep it stable. All of the devices used during this process are fixed to guarantee precise matching between the LED die and the PCB pad. The whole fabrication has been finished by only moving the PCB board using a precision linear translation stage. The PCB board is fixed and stabilized on the precision linear translation stage through which objects on its platform can be moved in XYZ
Figure 4.12. The printed circuit board of the supporting circuitry.

Figure 4.13. Different characters displayed using the LED array made by the OD-A20RF LED

direction by adjusting three micrometer heads. The main advantage using linear translation stage over manual operation is to create a highly stable environment in which the position of the PCB can be precisely controlled and determined. Once the PCB is fixed on the platform of the linear translation stage with tapes, several steps were taken to guarantee precise matching between the LED die and the PCB pad.
Figure 4.14. The experiment setup when the sensor works in the projection mode.

Figure 4.15. The experiment setup in an outdoor scenario when the sensor works in the energy harvesting mode. Note: This setup only shows components needed in the outdoor scenario but not real test
1. Dispensed a small drop of epoxy adhesive in the middle of the targeted PCB pad.

2. Placed an LED on a big pad except for that of interest with a precise tweezer and guaranteed the LED die having a good matching with the the pad and the LED n-type contact facing the specific direction.

3. Moved the targeted LED under the vacuum tip using the linear translation stage.

4. Leveled up the LED using the linear translation stage to make it touch on the tip and powered up the vacuum tip to such the LED up.

5. Leveled down the platform of the linear translation stage and guarantee the LED being fixed on the vacuum tip.

6. Moved the targeted big pad under the vacuum tip

7. Leveled up the PCB and attach the LED die to the targeted big pad

8. Leveled down the PCB with the attached LED and adjust the LED using the precise tweezzer

By repeating the same procedures, a 20x20 pixel array was fabricated as shown in Figure 4.6 (a) .

4.2.1.2. Wire Bond

This section describes the wire bonding technique which is used for connecting the LED n-type contact with the PCB small pad. Because the small pads and the LED n-type contacts are too small to be linked with regular wiring solutions, wire bonding techniques serve as the ideal method qualified for wiring process in our design. In this work, the ball bonding, one of the most popular bonding technique,
has been employed during the wire bonding process (Breach & Wulff, 2010). The Figure 4.9 shows the experimental setup for wire bonding. The device used to do this task is JPF wire bonder which creates welds at both ends of wire using a combination of pressure, heat, and ultrasonic energy. The second weld of the ball bonding can be placed along different direction while that of the other bonding techniques can only be placed in one direction. Therefore, the ball bonding is more preferable in our design. Six basic steps were taken in order to finish this process as it shown in Figure 4.10 (JPF Microtechnic, n.d.).

1. Started position operator of the JFP wire bonder and moved the targeted LED under the bond head.

2. Pressed the operation button to make the bond head travel down towards the LED.

3. Released the operation button and made the first bond on the LED n-type contact.

4. Clamp opened and the bond head rose back to its original position.

5. Started position operator again and move the small pad under the bond head.

6. Pressed the operation button again to make the bond head travel down towards the small pad.

7. Released the operation button and made the second bond on the PCB small pad.

Figure 4.11 shows several LEDs with finished wire bond. By repeating seven steps described above, the 20x20 pixel array has been fabricated in Figure 4.6 a). On the PCB board, 400 small PCB pads were designed to connect the LED cathodes. Each LED was bonded with the corresponding small PCB pad with golden wire 25 μm thick. Therefore, total 400 wires were used to fabricated entire 20x20 pixel array.
4.2.2 Pixel Array Fabrication with LXZ1-PH01 LED

The pixel array with LXZ1-PH01 LED is fabricated by soldering with solder paste. Considering the package around the LED die prevent it from the damage caused by high temperature, it is feasible to solder the LED on the targeted pad on the PCB. This method also avoids complicated procedure in the fabrication process with OD-A20RF LED. However, in order to maintain the compact design for the pixel array, the pads on the PCB are designed with the same size as the p-type contact and n-type contact respectively. Therefore, soldering with solder paste is more feasible than that with regular solders in our case. Several steps were taken to ensure a good matching between the LED contacts and the PCB pads.

1. Applied a layer of solder paste on the PCB through the stencil.

2. Put the PCB in the oven and heat it by following the solder heating profile specified in the datasheet.

3. Attached the LED on the PCB pad with correct direction and heated the targeted pad for a little while with the hot air gun

4. checked the connection between the LED contacts and the PCB pads by shaking the LED with a little force

4.3 The printed circuit board components

A picture of the printed circuit board (PCB) designed for the supporting circuitry of the sensor is illustrated in Figure 4.12. And the schematic and PCB layout design of the supporting circuitry is attached in Appendix Figure B.3 and Figure B.4.

The main components on the PCB consists of a fixed voltage regulator (Texas Instruments TPS797), an adjustable LDO (Micrel MIC39102), a DC/DC boost converter (Linear Technology LTC3105), a 8-bit digital-to-analog converter (DAC)
(Maxim Integrated MAX5385), a 12-bit analog-to-digital converter (ADC) (Texas Instruments ADC121S051), a transimpedance amplifier, a differential, twenty 3:1 multiplexers, twenty SPDT switches twenty MOSFET transistors, twenty 4:1 multiplexers and a FPGA module. The voltage regulator provides 3.3V analog power for all of the analog and mixed signal components on the board. The adjustable LDO provides 1.8V and 1.24V when the sensor is configured in the projection mode and sensing mode respectively. The LDO is disabled in the energy harvesting mode. The DC/DC boost converter converts voltages as low as 225mV to high voltages by adjusting its voltage control resistor. The transimpedance amplifier and differential amplifier in which photo-current gets amplified are constructed using two operational amplifiers (Texas Instrument OPA835). The digital-to-analog converter sets the positive terminal voltage of the transimpedance amplifier. The final analog voltage signal, which is proportional to the photo-current, is digitized by a 12-bit, 500KSPS, low power analog-to-digital converter. Four switching blocks through which the sensor are configured in different modes are made by the 3:1 multiplexer (NXP NX3L1G3157-Q100), the SPDT switch (NXP NX3L1G3157-Q100), the MOSFET transistor (Panasonic FC6943010R) and the 4:1 multiplexers (Analog Devices ADG804) respectively. All of digital control signals are generated by the FPGA (Xilinx XC3S500E). The Universal Asynchronous receiver/transmitter (UART) is chosen as the communication method between the FPGA and the computer.

4.4 Projection Experiment Setup

The experiment setup is shown in Figure 4.13 when a 9x9 LED-based pixel array made by the OD-A20RF LED is configured in the projection mode. The whole setup consists of the sensor system, a power supply board from DIGILENT and a PC with installed software to control the power board, the FPGA module and UART communication. The power supply board is used for powering up all discrete
components in the sensor system. This experiment indicates the feasibility of operating the pixel array made by the OD-A20RF LED in the projection mode. However, the 20x20 LED array made by the OD-A20RF LED is not robust enough to the vibration induced by frequent movement of the sensor system and adjustment of the 3D printed lens tube during the experiment. The vibration might cause the physical separation between the wire and the PCB pad. And fabrication cost of the LED array is so high that duplicating another LED array is inadvisable. Therefore, rest of other experiments were carried out with the pixel array made by the LXZ1-PH01 LED. The experiment setup for the sensor made by the LXZ1-PH01 is shown in Figure 4.14 when the sensor is configured in the projection mode. The whole setup consists of a white target screen, the sensor hardware, a power supply board and a PC. The images generated by the LED array are projected on the white screen via a single double-convex lens with 63 mm diameter and 48 mm focal length (Anchor Optics, 2012). The lens was outfitted in a 3-D printed lens tube. The complete design of the lens tube can be found in the Appendix Figure B.4, Figure B.5 and Figure B.6. The lens tube was able to adjust the distance between lens and the sensor ranging from 0 to 15 mm. The screen is placed 9 inches away from the sensor for high-quality projection. In the experiment, the images projected on the screen are made of 400 pixel units. Each pixel is corresponding to a lighten LED. By dividing the dimensions of the LED by that of pixel unit on the screen, the optical amplification can be determined. This experiment setup achieved an optical linear amplification of images by 1.5 X and optical density of 28.9 μW/cm², measured with the power sensor (Thorlabs S120C).

A VHDL code has been written to program the FPGA to generate control signals for the digital potentiometer, the row-level switching block, the column-switching block, the bank of MOSFET transistors and the bank of 4:1 multiplexers. The suggested coding procedure in the projection mode is described using Pseudo-code as follows:

1) initialize DAC, potentiometer
2) program potentiometer to output 30 Kohms
3) store image information in the internal memory
   (the memory has 20 vector and each vector has 20 bits)
4) for n = 1 to 20 (n is enabled row number)
   enable the row in the array with specified row number
   enable the columns in the array with information from the memory
   end
5) go to step (4)

4.5 Energy Harvesting Experiment Setup

The photovoltaic performance of the LED array was evaluated by measuring the array's current-to-voltage (I-V) curve. The I-V curve was measured outdoors in a sunny day. As shown in Figure 4.15, the whole setup consists of the sensor hardware, a power supply board, a source-meter (Keithley), a lux-meter and a PC with specific software to control the source-meter and the FPGA module. The probes of source-meter are connected to the LED anodes through the row-level switches and the LED cathodes through the column-level switches and the MOSFET transistors respectively. The source-meter provides a sweeping voltage from 0V to 1.5V in a incremental step and read the corresponding current in a loop based on each voltage value. The current and voltage data collected by the source-meter is then extracted in a text file and plotted as an I-V curve using MATLAB. The FPGA module sends control signals to the row-level switches, the column-level switches and the MOSFET transistors and configures the whole pixel array in the energy harvesting mode. This experiment aims to evaluate how much solar energy can be converted by the pixel array when the array faces to the sun with or without lens mounted. In this scenario, the experimental setup was built in a sunny day at 2 PM. The lux meter detected sun light with 115500 lux shined on the surface of the sensor. According to scientific data provided by the Environment
Growth Chambers, 1 lux sunlight can be roughly converted to optical power density of 4.02 W/m² (Environmental Growth Chambers, 2016). Therefore, with 115500 lux detected by the lux meter, light with power density of roughly 0.46 mW/mm² reached on the surface of the sensor. Because the effective absorption area of the LXZ1-PH01 LED is 1 mm². The total effective light reception area of the sensor is 400 mm². In the experiment, the total optical power then reached on the surface of the sensor was around 184 W/mm². In the experiment, the I-V curve was measured with the source meter and corresponding P-V curve was calculated and plotted using MATLAB in Figure 4.16. The MATLAB code can be found in the Appendix Chapter D. By analyzing the P-V curves as illustrated at the beginning of this chapter, the maximum power of 16.2 mW could be harvested by the sensor without lens mounted. Therefore, 0.09 % conversion efficiency could be achieved by the sensor. By comparing the experimental results in the outdoor scenario and indoor scenario, it is can be seen that LEDs are only highly sensitive to the light with narrow emission wavelength. The proposed experimental setup did not test the energy harvesting capability of the sensor with lens. Therefore, in the future work, this experiment will aims to evaluate how much power can be harvested when the sensor is mounted with lens. And a large quantity of tests will be carried out to analyze the relation between the pixel-array harvesting capability and distance away from the lens.

4.6 Image Sensing Experiment Setup

To test the prototype in the image sensing mode, a object consisting of a white square paper on a black background was placed in front of the LED-based image sensor. According to the principle of reversibility of the light, the object should be positioned at the place where sharp images can be projected in the projecting setup. Hence, the object can always stay in focus and the image of it can be clearly captured by the sensor. Figure 4.17 shows the experimental setup for the imaging
mode and image captured using this setup. The size of the object is illustrated in Figure 4.17. The distance of lens is 99 mm away from the object and 90 mm away from the pixel array. A VHDL code has been written to digitize the optical image sensed by the sensor and send the digitized image to the PC for display (Appendix). The coding procedure in the projection mode is described as follows:

1) initialize ADC, DAC
2) program DAC to output 1.7 V
3) for $n = 1$ to 20 ($n$ is enabled row number)

    for $m = 1$ to 20 ($m$ is enabled column number)

        read transimpedance output using ADC

        send digitally readout signals to the PC through UART

    end

end

the complete VHDL code can be found in the Appendix. A MATLAB script has been written to display the digitized images. In the experiment, the object was projected on the pixel array through the lens. The optical image of the object covered a area which had the same shape as that of the object on the pixel array. In this area, each LED sensed a small portion of this optical image and converted it to a proportional electric signal. The sensor digitized the optical image projected on the pixel array and then transmitted digitized image information to the PC. the MATLAB was used to display digitized value in gray scale from each pixel and construct entire image digitally which was read out from the sensor. Therefore, the optical image was correspondingly mapped to a image display field with 20x20 pixel array. As can be seen from Figure 4.17, the shape of the object is the same as that of image displayed through MATLAB. The complete MATLAB script can be seen in the Appendix. However, apparent variations between pixels can be easily
observed from the displayed image in Figure 4.17 when images are captured under the uniform light. This phenomenon refers to the distorted photocurrent signal to which noises from the external environment are coupled. The noises with frequencies ranging from 57 Hz to 62 Hz were characterized using oscilloscope when observing the output of current amplifier. Therefore, the narrow-band notch filter, which is used to attenuate noises with specific range, has been designed in our system. Figure 4.18 shows the images captured after applying notch filter at the output of the current amplifier. As can be seen from the picture, the noise, which is referred to gray-scale variations between pixels in the images, can be greatly removed after applying the notch filter.

4.7 Limitations

This section describes the main limitation on the system performance and their corresponding solutions. The main limitation comes from the experimental results that the coding technique used in typical image sensor can not applied in the passive LED-based pixel array with cathodes connected in a column and anodes connected in a row. As a result, only images with square shape can be captured using current operation method. A 2x2 LED-based array with its equivalent circuit in Figure 4.19 has been used to analyze the limitation with current operational method in the image sensing mode. The LED in black denotes it is receiving light. As it is illustrated in Figure 4.19, the photo-current can be generated by the LED2 if the light is shining on it. However, If we still want to read photocurrent from the LED2 with light shining on the LED1 and LED4 instead, a current flow will be created across the LED3 and be mistaken for the photocurrent generated by the LED2 as shown in Figure 4.19, even though there is no current across the LED2 in this case. Because the cathode of the LED1 and LED4 are left floating, they get charged under illumination and the voltage difference between their anodes and cathodes is about 1.33V. Therefore, the voltages at the anode of LED4 and the cathode of
LED1 become \( V_{ref} \) and -1.33V respectively and the difference between these two voltages will forwardly bias the LED3 to generate current flow. This limitation could be eliminated by changing the operational method by applying an extra voltage \( V_a \) at the cathode of LED1. The voltages of \( V_a \) should be correspondingly changed in different situations when light is shining on different LEDs.

- \( V_a > V_{ref} + 1.33V \) when the LED4 is receiving light. Figure 4.20 shows the 2x2 LED array operating in this situation. Because the cathode of LED4 is floating, its voltage will become \( V_{ref} \) when the LED4 is receiving light. Because the voltage at the cathode of LED3 is larger than that at the anode, the LED3 is reversed biased. No current will be generated by the LED3 because of no light on it.

- \( V_a < V_{ref} + 1.33V \) when the LED3 is receiving light. Figure 4.21 shows the 2x2 LED array operating in this situation. Because the cathode of LED3 is floating, its voltage will become \( V_a + 1.33V \) because of the light on it. Due to the larger voltage at the cathode of LED4 than that at the anode, the LED4 is reversed biased. No current will be generated across the LED4 when it is in dark.

- \( V_a = V_{ref} + 1.33V \). In this situation, both of the LED3 and LED4 are receiving light. Because voltages increased at the anode of LED3 and LED4 are canceled with each other. No current will be generated across these two LEDs.

As can be seen in the operational method mentioned above, the \( V_{ref} \) is the only variable which is controlled by the DAC. Therefore, images could be captured in this configuration by only adjusting the output of the DAC. The passive 20x20 pixel array is equivalent to a 2x2 pixel array. Therefore, this method is also feasible when operating 20x20 pixel array to capture different images.
4.8 Summary

In this chapter, tests on the proposed LED-based image sensor with image sensing and energy harvesting capabilities were carried out successfully in different experimental setups. The results show the image sensor can be used to capture and project images through a double convex lens. In addition, the best photovoltaic performance can be achieved when the sensor is illuminated under specific wavelength of light.
Figure 4.16. The I-V curve and P-V curve of the pixel array when it is pointed to the sun in an outdoor scenario. a) the I-V curve measured without lens mounted and b) the P-V measured without lens mounted.
Figure 4.17. The experimental setup for the imaging mode and corresponding image captured by the sensor.
Figure 4.18. The captured image after applying the notch filter. Note, the experimental setup for this image is different from that in Figure 4.17.

Figure 4.19. The 2x2 pixel array configuration with its equivalent circuit. Only LED2 is receiving light.
Figure 4.20. The 2x2 pixel array configuration with its equivalent circuit. Only LED4 are receiving light.

Figure 4.21. The 2x2 pixel array configuration with its equivalent circuit. Only LED3 are receiving light.
Figure 4.22. The 2x2 pixel array configuration with its equivalent circuit. Only LED3 and LED4 are receiving light.
CHAPTER 5. CONCLUSIONS AND FUTURE WORKS

The light emitting diode (LED) technology has seen great improvements in efficiency and cost reduction. These advances have been further promoted by diverse and wide-spread applications. Because an LED is basically a p-n junction, its capability of sensing light and harvesting energy has been found and explored for many years. The rapid developments of LED technology make it possible to use LEDs in a variety of applications, such as visible light communication, projection, and optically powered Microsystems. Meanwhile, wide-spread use of LEDs has further propelled the multiple functionalities of LEDs achieved in one system.

In this thesis, An LED-based image sensor with energy harvesting, image sensing and projection capabilities has been designed and tested. This triple functionality is achieved by employing light emitting diodes (LEDs), which can emit and absorb light depending on their bias conditions, to implement the pixels in the sensor. A proof-of-concept prototype was built and tested. The experimental measurements and data analysis were carried out on the sensor. The VHDL code and MATLAB script were written to configure the sensor in different working modes. The results are sufficient to answer the research questions associated with this thesis. Firstly, the image sensor is proven to be able to sense and capture images under different light conditions. The images can be easily distinguished from the background and their qualities are greatly improved after applying a notch filter at the output of current amplifier. Secondly, the sensor can either work in three different modes individually or combine projection mode and imaging mode together based on the configuration of the sensor. The performances of the sensor working in three modes are evaluated individually. When the sensor works in the projection setup, a linear amplification of the LEDs by 1.5 X and optical density of 28.9 $\mu$W/cm$^2$ were achieved on screen around 9 inches away from the lens system. In
addition, the sensor can harvest 16.2 mW of power when all of LEDs are configured into energy harvesting mode, which also answers the third question in the thesis. The harvested energy are sufficient to power the self-powered microsystem and more energy can be harvested with more LEDs incorporated in the pixel array.

5.1 Future Works

While this thesis has demonstrated the capabilities of operating the proposed sensor to project image, sense image and harvest energy, many opportunities for extending the scope of this thesis remain. The future work presents what experiments needs to be performed. Firstly, the operational method might be changed in order to improve the performance of the sensor. This purpose can also be done by changing the hardware design for the pixel array. Moreover, the 20x20 pixel array made by the OD-A20RF LED also needs to be tested in three different modes including energy harvesting mode, image sensing mode and projection mode. For these modes, experimental tests should be conducted to further validate the findings with additional data.
APPENDICES
### APPENDIX A

<table>
<thead>
<tr>
<th>LED brand</th>
<th>emission wavelength</th>
<th>size</th>
<th>package</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD-A20RF</td>
<td>617 nm</td>
<td>0.5 mm x 0.5 mm</td>
<td>no</td>
</tr>
<tr>
<td>LXZ1-PH01</td>
<td>617 nm</td>
<td>1.7 mm x 1.3 mm</td>
<td>yes</td>
</tr>
</tbody>
</table>

Figure 1. The comparison between the OD-A20RF LED and the LXZ1-PH01 LED
Figure 2. PCB layout for the LED array made by the OD-A20RF LED
Figure 3. PCB layout for the LED array made by the LXZ1-PH01 LED
Figure 4. schematic of the sensor supporting circuit
Figure 5. PCB layout of the sensor supporting circuit
Figure 6. schematic of the lens part 1
Figure 7. schematic of the lens part 2
Figure 8. schematic of the lens part 3
APPENDIX C

library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.STD_LOGIC_UNSIGNED.ALL;
use IEEE.NUMERIC_STD.all;
--use IEEE.STD_LOGIC_ARITH.all;
use std.textio.all;
use ieee.std_logic_textio.all;

entity top is
  generic
    NUM_ROWS : natural := 30;
    NUM_COLS : natural := 30;
    FSM_CLK_DIV_2 : natural := 100000; -- FSM_CLK should be
    faster than the RAC_CLK, ADC_CLK and POT_CLK;
    UART_CLK_DIV_2 : natural := 50000; -- 2004-9600 bps,
    UART_16MCLK_DIV_2 : natural := 163; -- 163-9600 bps,
    UART_10MCLK_DIV_2 : natural := 163; -- 163-9600 bps,
    UART_15MCLK_DIV_2 : natural := 163; -- 163-9600 bps,
    UART_115200bps : natural := 115200; -- 115200 bps,
    UART_230400bps : natural := 230400; -- 230400 bps,
    UART_460800bps : natural := 460800; -- 460800 bps,
    UART_921600bps : natural := 921600; -- 921600 bps,
    UART_1843200bps : natural := 1843200; -- 1843200 bps,
    UART_3686400bps : natural := 3686400; -- 3686400 bps,
    UART_7372800bps : natural := 7372800; -- 7372800 bps,
    UART_14745600bps : natural := 14745600; -- 14745600 bps,

    peripherals must be greater than speed of UART!
    ADC_CLK_DIV_2 : natural := 50000;
    POT_CLK_DIV_2 : natural := 50000;

  port (CLX : in STD_LOGIC;
        RST : in STD_LOGIC;
        LED : out STD_LOGIC_VECTOR(3 downto 0);
        COL_SW : out STD_LOGIC_VECTOR(19 downto 0);
        COL_PED : out STD_LOGIC_VECTOR(19 downto 0);
        ROW_SW : out STD_LOGIC_VECTOR(19 downto 0);
        DEC_SW : out STD_LOGIC;
        ENC_SW : out STD_LOGIC;
        MUX_A : out STD_LOGIC_VECTOR(4 downto 0);
        MUX_B : out STD_LOGIC_VECTOR(4 downto 0);
        MUX_C : out STD_LOGIC_VECTOR(4 downto 0);
        POT_CS : out STD_LOGIC;
        POT_SCL : out STD_LOGIC;
        POT_SDA : out STD_LOGIC;
        DAC_CS : out STD_LOGIC;
        DAC_SCL : out STD_LOGIC;
        DAC_SDA : out STD_LOGIC;
        ADC_CS : out STD_LOGIC;
        ADC_SCL : out STD_LOGIC;
        ADC_SDA : out STD_LOGIC;
        UART_TXD : out STD_LOGIC;
        UART_RXD : in STD_LOGIC;
        CLK_P : out STD_LOGIC;
        CLK_N : out STD_LOGIC;
        CS_P : out STD_LOGIC;
        CS_N : out STD_LOGIC;
        ADDR : out STD_LOGIC;
        ADDR_OUT : out STD_LOGIC);

end top;
architecture behavioral of top is

-- component declaration --
component ADC/drivers is
  port(RST : in STD_LOGIC; -- global reset
    CLK : in STD_LOGIC;
    SCLK : out STD_LOGIC; -- connect this signal to the ADC clock
    CS : out STD_LOGIC;
    SDO : in STD_LOGIC;
    START : in STD_LOGIC; -- a low-to-high transition of SCLK starts
    DONE : inout STD_LOGIC; -- goes high at the end of the reading
    DATA : out STD_LOGIC_VECTOR(11 downto 0));
end component;

component MAX3265 is
  port(CLK, RST : in STD_LOGIC;
    DIN : out STD_LOGIC;
    START : in STD_LOGIC;
    CS : out STD_LOGIC;
    SCLK : out STD_LOGIC;
    DONE : inout STD_LOGIC;
    DATA : in STD_LOGIC_VECTOR(7 downto 0));
end component;

component MAX5484 is
  port(CLK, RST, CS, SCLK : out STD_LOGIC;
    DONE : inout STD_LOGIC;
    START : in STD_LOGIC;
    DATA : in STD_LOGIC_VECTOR(9 downto 0));
end component;

component uart_tx is
  port(CLK, RST : in std_logic;
    DATA : in std_logic_vector(7 downto 0);
    TXD, CTS : out std_logic);
end component;

component uart_rx is
  port(CLK, RST : in std_logic;
    RXD, DTR : in std_logic;
    DATA : out std_logic_vector(7 downto 0);
    RX READY : out std_logic;
    PARITY_OK : out std_logic);
end component;

component decoder5x29 is
  port (d : in STD_LOGIC_VECTOR(4 downto 0);
    enable : in STD_LOGIC;
    y : out STD_LOGIC_VECTOR(19 downto 0));
end component;
end component;

--------------- end component declaration ---------------
signal LEDOn : std_logic_vector(3 downto 0);

---- signals for DAC --------------------
signal dac_start : std_logic;
signal dac_data : std_logic_vector(7 downto 0);
signal dac_ready : std_logic;

---- signals for ADC --------------------
signal adc_start : std_logic;
signal adc_data : std_logic_vector(11 downto 0);
signal adc_ready : std_logic;
signal ADC_CS, CPV : std_logic;

---- signals for POT ---------------------
signal pot_start : std_logic;
signal pot_data : std_logic_vector(9 downto 0);
signal pot_ready : std_logic;

---- signals for UART -------------------
signal uart_send : std_logic; -- uart start to transmit data when the
signal goes high
signal uart_cts : std_logic; -- flag bit indicating uart finishes
transmission(internally)
signal uart_tx_data : std_logic_vector(7 downto 0); -- input data vector to
uart
signal uart_dtr : std_logic;
signal uart_rx_data : std_logic_vector(7 downto 0);
signal uart_rx_ready : std_logic;
signal uart parity ok : std_logic;

---- clock signals ----------------------
signal fsck_clk, uart_clk, uart_166clk, dac_clk, adc_clk, pot_clk : std_logic;

---- signals for main FSM ---------------
type TState is (IDLE, COMM0, COMM1, COMM2);
type IconState is (IDLE, COMM0, COMM1, COMM2);
signal state, return_state : TState;
signal icon_state : IconState;
signal com_byte0, com_byte1 : std_logic_vector(7 downto 0);
signal col_vector, row_vector : std_logic_vector(4 downto 0);
signal dec col sv, dec row sv : std_logic_vector(9 downto 0);
signal enable_col dec, enable_row dec : std_logic;
signal NODE : std_logic_vector(1 downto 0);
signal A4, A3, A2, A1, A0 : std_logic;
--- signals for display -----------------------------
signal trigger, clear_trigger : std_logic;
signal go_mode, clear_go_mode : std_logic;

type Teamory is array (0 to NUM_ROWS-1) of std_logic_vector(7 downto 0);
type Thit_array is array (0 to NUM_ROWS-1) of std_logic_vector(NUM_COLS-1 downto 0);
signal bit_array : Thit_array; -- array of bits containing state of LEDs (1:ON, 0:OFF). In the future we could use the full byte

-- information from memory to set LED intensity (using PWM)

-- impure function init_mem(file_name : in string) return Teamory is
  -- file mif_file : text open read_mode is mif_file_name;
  -- variable mif_line : line;
  -- variable temp_bw : bit_vector(7 downto 0);
  -- variable temp_mem : Teamory;
  -- begin
  --  for i in Teamory'range loop
  --    readfile(mif_file, mif_line);
  --    read(mif_line, temp_bw);
  --    temp_mem(i) := to_std_logic_vector(temp_bw);
  --  end loop;
  --  return temp_mem;
  -- end function;
-- signal memory : Teamory := init_mem("stripes.txt");

impure function InitMemFromFile (MemFileName : in string) return Teamory is
  variable MemFileLine : line;
  variable mem : Teamory;
  begin
    for i in Teamory'range loop
      readFrom(MemFileName, MemFileLine);
      mem(i) := to_std_logic_vector(MemFileLine);
    end loop;
  end function;
signal memory : Teamory := InitMemFromFile("white.txt");

begin
  CLK_CPY <= sysclk;
  NO_CPY <= (not A0) XOR net1;
  A1_CPY <= not A1;
  ADC_CS <= ADC_CS_CPY;
  ADC_CS_OU <= ADC_CS_CPY;
  LEDS <= not LEDSn;
  COL_SW <= not dec_col_sw;
  ROW_SW <= dec row_sw;

Page 4
A4 <= col_vector(4);
A3 <= col_vector(3);
A2 <= col_vector(2);
A1 <= col_vector(1);
A0 <= col_vector(0);
MUX_A1 <= (others => (not A0) XOR A1);
MUX_A0 <= (others => (not A1));
MUX_EN(0) <= (not A4) AND (not A3) AND (not A2);
MUX_EN(1) <= (not A4) AND (not A3) AND (not A2);
MUX_EN(2) <= (not A4) AND (not A3) AND (not A2);
MUX_EN(3) <= (not A4) AND (not A3) AND (not A2);
MUX_EN(4) <= (not A4) AND (not A3) AND (not A2);

--- FSM implementation ---------------------------------------------

PROCESS (fsm_clk, RST)
  BEGIN
    state <= IDLE;
    return_state <= TRAP;
    uart_send <= "0";
    uart_tx_data <= "000000001";
    pot_start <= "0";
    pot_data <= (others => '0');
    dec_start <= "0";
    dec_data <= (others => '0');
    adc_start <= "0";
    MEMO <= "0000";
    col_count <= 0;
    row_count <= 0;
    enable_col_dec <= "0";
    enable_row_dec <= "0";
    DDEC_SW <= "0";
    COL_SET <= (others => '0'); -- turn off MOSFETs upon reset
    NODE <= "01";
    clear_trigger <= "0";
    clear_go_mode <= "0";
    adc_count <= 0;
    IF (rising_edge (fsm_clk)) THEN
      CASE state IS
        genscript
WHEN IDLE =>
  state <= MODE0;
  LEDs0 <= "0000";
WHEN MODE0 =>
  clear_go_node <= '0';
  if(combo_byte0 = 'x"59") then
    state <= IMG0;
    elsif(combo_byte0 = 'x"54") then
      state <= DSP0;
      elsif(combo_byte0 = 'x"53") then
        state <= MGED;
      end if;
  -- if(MODE = "00") then -- energy harvesting node
  --  state <= EN0;
  --  elsif(MODE = "01") then -- imaging node
  --    state <= IMG0;
  --  else
  --    state <= DSP0;
  --  end if;
  LEDs0 <= "0001";

  -- beginning of BARTESTING node ---------------------
  -- energy harvesting node
  DCDC_SW <= '1';
  enable_row_dec <= '0'; -- force ROW_SV to 1 -> connect rows
to DC-DC converter
  enable_col_dec <= '0'; -- force COL_SV to 0 -> connect
columns to NOSFETS
  COL_FET <= (others => '1'); -- connect LEDs' cathodes
to GND
  state <= POST0;
  get_data <= std_logic_vector(to_unsigned(0, 10)); -- set
  LDO to minimum output
  return_state <= EN0;
  LEDs0 <= "0010";
  -- add line to disable LDO
WHEN EN0 =>
  state <= DC0;
  dec_data <= std_logic_vector(to_unsigned(0, 8));
  -- Ref=0.9*MVDG=0.9*2.3=2.97
  return_state <= TRAP;
  LEDs0 <= "0011";

  -- end of BARTESTING node --------------------------

  -- beginning of IMAGING node ---------------------
  WHEN IMG0 =>
  imaging_node
  adc_count := 0;
  col_count := 0;
  row_count := 0;
  enable_col_dec <= '1';
enable_row_dec <= '1';
COL_SEL <= (others => '0');
DDC_SW <= '0';
state <= P070;
-- program adjustable LED's potentiometer
pot_data <= std_logic_vector(to_unsigned(0, 10));
return_state <= IMG1;
LEDn <= "0010";
WHEN IMG1 =>
  program IMG;
state <= IMG0;
dec_data <= std_logic_vector(to_unsigned(0b10, 8));
Yref(0:9) <= (Yref(0:9));
return_state <= IMG3;
LEDn <= "0011";
WHEN IMG2 =>
  if (go_mode = '0') then
    if (trigger = '1') then
      clear_trigger <= '1';
      state <= IMG3;
    else
      state <= IMG2;
      end if;
  else
    state <= MODE0;
    clear_go_mode <= '1';
    end if;
    LEDn <= "0011";
WHEN IMG3 =>
  row_vector <= std_logic_vector(to_unsigned(row_count, 31));
col_vector <= std_logic_vector(to_unsigned(col_count, 31));
state <= ADC_CNT;
WHEN ADC_CNT =>
  adc_count := adc_count + 1;
  if (adc_count = 51) then
    state <= IMG4;
    adc_count := 0;
  else
    state <= ADC_CNT;
    end if;
WHEN IMG4 =>
  A/D conversion
  adc_start <= '1';
  state <= IMG5;
  LEDn <= "0100";
WHEN IMG5 =>
  if (adc_ready = '0') then
    -- wait until controller pulls up
    DONE/READY output
    state <= IMG5;
    end if;
else
    adc_start <= '0';
    uart_tx_data <= adc_data[11 downto 4];
    state <= IMG5;
end if;
    LEDStr <= "0101";

WHEN IMG6 =>
    uart_send <= '1';
    state <= IMG7;
    LEDStr <= "0110";

WHEN IMG7 =>
    if(uart_cts = '0') then -- wait until UART controller pulls
        up CTS output
        state <= IMG7;
    else
        uart_send <= '0';
        uart_tx_data <= "0000" & adc_data[3 downto 0];
        state <= IMG8;
    end if;

WHEN IMG8 =>
    uart_send <= '1';
    state <= IMG9;

WHEN IMG9 =>
    if(uart_cts = '0') then -- wait until UART controller
        pulls up CTS output
        state <= IMG9;
    else
        uart_send <= '0';
        col_count := col_count + 1;
        if(col_count = NUM_COLS) then
            col_count := 0;
            row_count := row_count + 1;
            if(row_count = NUM_ROWS) then
                row_count := 0;
                state <= IMG2;
                clear_trigger <= '0';
            else
                state <= IMG3;
            end if;
        else
            state <= IMG3;
        end if;
    end if;
    LEDStr <= "0111";
end if;

--- end of IMAGING mode -------------------

--- beginning of DISPLAY mode --------------
WHEN DISPLAY =>
    projection/display mode
col_count := 0;
row_count := 0;
enable_col_dec <= '0'; -- force all COL_SW to select VO input (toward MOSFETs)
col_vector <= "00000";
enable_row_dec <= '1';
COL_PET <= (others => '0'); -- turn off MOSFET at the beginning
DCCD_SW <= '0';
state <= P07;
-- program adjustable
LDD's potentiometer
get_data <= std_logic_vector(to_unsigned(500, 10));
return_state <= DISP1;
LEBn <= "0010";

WHEN DISP1 =>
begin
program DMZ
state <= DM0;
dc_data <= std_logic_vector(to_unsigned(60, 8));
-- Vref=0.94V06/0.94V1.1-5.97
return_state <= DISP2;
LEBn <= "0011";

WHEN DISP2 =>
begin
-- load contents of bit_array from memory
tmp_byte <= memory(row_count+NUM_COLS+col_count);
tmp_vector(col_count) := tmp_byte(7) or tmp_byte(6) or tmp_byte(5) or tmp_byte(4)

WHEN DISP3 =>
begin
if go_mode = '0' then
COL_PET <= bit_array(row_count);
row_vector <= std_logic_vector(to_unsigned(row_count, 5));
state <= DISP4;
else
get_data <= std_logic_vector(to_unsigned(0, 10));
state <= P06;
end if;
end if;
123
return_state <= MODE0;
clear_go_mode <= '1';
end if;

when DISP4 =>
row_count := row_count + 1;
if (row_count = NOW_RMS) then
row_count := 0;
end if;
state <= DISP3;
LEDSn <= '0'1';
end of DISPLAY mode

--- programming of digital potentiometer ---
when POTO =>
pot_start <= '1';
state <= POTO;

when POTO1 =>
if (pot_ready = '0') then
wait until controller pulls up
DONE/READY output
state <= POTO1;
else
pot_start <= '0';
state <= return_state;
end if;

--- programming of DAC ---
when DACO =>
dac_start <= '1';
state <= DAC1;

when DAC1 =>
if (dac_ready = '0') then
wait until controller pulls up
DONE/READY output
state <= DAC1;
else
dac_start <= '0';
state <= return_state;
end if;
when TRAP =>
state <= TRAP;
LEDSn <= "1111";
end case;

== COL_FET <= col_fet_var;
col_vector <= std_logic_vector(to_unsigned(col_count, 5));

row_vector <= std_logic_vector(to_unsigned(row_count, 5));
end if;
end PROCESS;
--- end FSM implementation ---
--- COMM implementation ---

PROCESS (RST, CLK)
BEGIN
  if RST = '0' THEN
    comm_state <= COMM;
    uart_dtr <= '0';
    go_node <= '0';
  ELSIF rising_edge (CLK) THEN
    if (clear_go_node = '1') then
      go_node <= '0';
    end if;
    if (clear_trigger = '1') then
      trigger <= '0';
    end if;
    CASE comm_state IS
      WHEN 'TILE' =>
        comm_state <= COMM;
      WHEN 'COMM1' =>
        if (uart_rx_ready = '1') then -- something has arrived
          comm_state <= COMM1;
          uart_dtr <= '0'; -- DTR low to clear RX_READY
          comm_byte9 <= uart_rx_data;
        else
          comm_state <= COMM1;
        end if;
      when 'COMM2' =>
        if (uart_rx_ready = '1') then -- wait until RX_READY goes back to low
          comm_state <= COMM1;
        else
          uart_dtr <= '1'; -- enable reception again
          comm_state <= COMM2;
        end if;
      when 'COMM3' =>
        if (uart_rx_ready = '1') then
          comm_state <= COMM3;
        else
          comm_state <= COMM3;
        end if;
      end CASE;
    end IF;
  end IF;
END;
```
--
-- comm_state <= COMM1;
--
-- end if:
when COMM2 =>
  if(com_byte0 = 'x'99') then
    trigger <= '1';
  elsif(com_byte0 = 'x'53') then
    go_mode <= '1';
  end if:
  comm_state <= COMM3;

END CASE;
END PROCESS;

--- END COMM implementation ---------------

U1: ADC121004 port map (  
  RST => RST,  
  CLK => adc_clk,  
  SD0 => ADC_SDO,  
  START => adc_start,  
  DATA => adc_data);

U2: MAX396 port map (  
  CLK => dac_clk,  
  RST => RST,  
  DIN => DAC_DIN,  
  START => dac_start,  
  DATA => dac_data);

U3: MAX440 port map (  
  CLK => pot_clk,  
  RST => RST,  
  DIN => POT_DIN,  
  CS => POT_CS,  
  SCLK => POT_SCLK,  
  DATA => pot_data);

U4: uart_tx port map (  
  CLK => uart_clk,  
  RST => RST,  
  SE0 => uart_send,  
  DATA => uart_tx_data,  
  TXD => UART_TXD,  
  RTS => uart_cts);

U5: uart_rx port map (  
```
RST => RST,
  CLK => uart_16xclk,
  RXD => UART_RXD,
  DTR => uart_dtr,
  DATA => uart_rx_data,
  RX READY => uart_rx_ready,
  PARITY_OK => uart_parity_ok;

U6: decoder6x20 port map (
  d => col_vector,
  enable => enable_col_dec,
  y => dec_col_sw);

U7: decoder6x20 port map (
  d => row_vector,
  enable => enable_row_dec,
  y => dec_row_sw);

**clock generation**

```vhdl
process (CLK, RST)
begin
  if RST = '0' then
    fsm_clk <= '0';
    uart clk <= '0';
    uart_16clk <= '0';
    adc clk <= '0';
    pot clk <= '0';
    fsm_counter <= 0;
    uart_counter <= 0;
    uart_16counter <= 0;
    adc_counter <= 0;
    pot_counter <= 0;
  elsif (rising_edge(CLK)) then
    if (fsm_counter = FSM_CLK_DIV_2) then
      fsm_clk <= not fsm clk;
      fsm_counter <= 0;
    end if;
end if;
end process;
```
if(uart_counter = UART_CLK DIV 2) then
  uart_clk <= not uart_clk;
  uart_counter := 0;
end if;

if(uart_16xcounter = UART_16XCLK_DIV 2) then
  uart_16xclk <= not uart_16xclk;
  uart_16xcounter := 0;
end if;

if(dac_counter = DAC_CLK_DIV 2) then
  dac_clk <= not dac_clk;
  dac_counter := 0;
end if;

if(adc_counter = ADC_CLK_DIV 2) then
  adc_clk <= not adc_clk;
  adc_counter := 0;
end if;

if(pot_counter = POT_CLK_DIV 2) then
  pot_clk <= not pot_clk;
  pot_counter := 0;
end if;
end process;

--- end clock generation -------------------------------

end behavioral;
APPENDIX D

function varargout = camera_gui(varargin)

gui_Singleton = 1;

if nargin & strcmp(varargin{1})
    gui_Singleton = gui_Singleton芷varargin{1});
end

gui_main = struct('gui_Name', 'filename', ...
    'gui_Singleton', gui_Singleton, ...
    'gui_OpeningFun', @Main, ...
    'gui_OpenFun', @MainWindow, ...
    'gui_CloseFun', @Main, ...
    'gui_DelayFun', ());

if nargin
    if nargin == 1
        varargout{1} = gui_main(varargin{1});
    else
        gui_main(varargin{1});
    end
end

% --- uonacti before camera_gui is mad visible.

function Main, @MainWindow)

global NROWS;

global NCOLS;
global F$rector_alignment;

global F$rector_image;

global F$MM1;

NROWS = 20;
NCOLS = 20;

F$rector_alignment = zeros(NROWS, NCOLS);

F$rector_image = zeros(NROWS, NCOLS);

F$MM1 = zeros(NROWS, NCOLS);

end

function button_modified!object, eventdata, handle)

varargout{1} = handle.outputs

function button_connect_Callback@object, eventdata, handle)

end

image = get(handle, edit_oom_port, 'String');
handle.serial_obj.Port = com_str;
foreach(handle.serial_obj):

    if handle.serial_obj.Status == "open"
        set(handle.text_status, 'string', 'Failed to open serial port');
        set(handle.button_disconnect, 'enable', 'off');
        set(handle.button_connect, 'enable', 'on');
        set(handle.button_info, 'enable', 'off');
    else
        set(handle.text_status, 'string', 'COM port opened successfully');
        set(handle.button_disconnect, 'enable', 'off');
        set(handle.button_connect, 'enable', 'on');
        set(handle.button_info, 'enable', 'on');

    end

guiEvalObject, handled;

function edit_COMM_port_Callback(hObject, eventdata, handles)

function edit_COMM_port_Cross柝 From (Object, eventdata, handled)
if(hObject == get(hObject, 'BackgroundColor'))
    set(hObject, 'BackgroundColor', 'white');
end

function button_disconnect_Callback(hObject, eventdata, handles)
    close(handle.serial_obj);
    set(hObject.text_status, 'string', 'COM port closed');
    set(hObject.button_disconnect, 'enable', 'off');
    set(hObject.button_connect, 'enable', 'on');
    set(hObject.button_info, 'enable', 'off');

guiEvalObject, handled;

% ----- Event on button press in button_info.
function button_info_Callback(hObject, eventdata, handles)
global MNN5;
global NUM3;
global FIL_vector_min8;
global FIL_vector_min12;
global FILARRAY;
global buffer;

    if(validate(handles.serial_obj) == 1)
        set(handles.button_info, 'enable', 'off');
        pause(50);
set(handles.button_map, 'String', 'on');

if handles.serial_obj.BytesAvailable >= 2^MODS4X0COLS
    buffer = read(handles.serial_obj, 2^MODS4X0COLS, 'uint8');
    % Read out pixel values in a vector
    PIX_vector_uint12 = zeros(1, 2^MODS4X0COLS);
    PIX_ARRAY = zeros(1, MODS4X0COLS);
    % First byte shift 4 bits to the left from second byte
    for i = 1:2^MODS4X0COLS
        if mod(i, 2) == 0
            PIX_vector_uint12(i) = buffer(i);
        else
            PIX_vector_uint12(i) = buffer(i) + 256;
        end
    end
    % Second byte shift 8 bits to the left from second byte
    for i = 1:MODS4X0COLS
        if mod(i, 2) == 1
            if (i >= 360)
                PIX_ARRAY(i) = 0;
            else
                PIX_ARRAY(i) = 600;
            end
            % for i = 1:MODS4X0COLS
            %     if (PIX_ARRAY(i) >= 3600)
            %         PIX_ARRAY(i) = 0;
            %     end
            % end
        end
    end
    % rearrange vector into image matrix
    PIX_MATRIX = reshape(PIX_ARRAY, MODS, MODS, 4);
    % show(PIX_MATRIX, [0 255]);
    imshow(PIX_MATRIX, [0 255]);
    % set(handles.text_status, 'String', sprintf('Displaying from %d of %d...','...max_frame'));
    else
        disp(sprintf('Available bytes does not match image size %d bytes available(%d)', handles.serial_obj.BytesAvailable));
        set(handles.text_status, 'String', sprintf('Bytes available from sensor = %d', handles.serial_obj.BytesAvailable));
    end
% —— Executes during object creation; after setting all properties.
function popen massekJ_CreateFUIObject (eventdata, handles)
if (isempty(get(hObject, 'BackgroundColor'))
  set(hObject, 'BackgroundColor', 'white');
end
%
% —— Executes on button press in pushbutton9.
function button9Callback(hObject, eventdata, handles)
    global Masses;
    global NODS;
    global FIX_vector_size;
    global FIX_vector_size12;
    global FIX_ARRAY;
    global buffer

    name = sprintf('file%d', frame);
    if (isempty(name))
        name = sprintf('frame%d', frame);
    saveframe(name, 'Masses', 'NODS', 'FIX_ARRAY', 'buffer', 'FIX_vector_size12');
end
%
% —— Executes on button press in pushbutton10.
function button10Callback(hObject, eventdata, handles)
    global Masses;
    global NODS;
    global FIX_vector_size;
    global FIX_vector_size12;
    global FIX_ARRAY;

    FIX_ARRAY = reshape(FIX_ARRAY, 1, NODS); %| FIX_VECTOR_SIZE|
    figure;
    hist(FIX_ARRAY, 100)
    S = ylim(FIX_ARRAY);
    L = max(max(FIX_ARRAY));
    x = linspace(FIX_ARRAY);
    title(sprintf('min = %.1f max = %.1f mean = %.1f', S, L, M));
    bar(x, S);
end
%
% —— Executes on button press in reset.
function button_resetCallback(hObject, eventdata, handles)
    write(hObject, serial_obj, 'N', 'size');
% --- Eventos de boton press in display.
function button_display_Callback(hObject, eventdata, handles)
    title(handles.serial_obj, 'Y', 'FontSize');
LIST OF REFERENCES
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