"Project Hummingbird"

Plenoptic Imaging for Industrial Inspection Product Requirements Document

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This has been approved by our customer (Dec.14, 2017).

Document Number 00005

Revisions Level	Date
E	12-14-2017

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Revision History

Rev	Description	Date	Authorization
A	Initial PRD Released	11-1-2017	All
B	Updated Vision Updated Fitness for Use Added Design Options	11-15-2017	All
C	Added Responsibilities Updated Design Options Added Preliminary Results	11-27-2017	All
D	Updated Preliminary Results Added Timeline	12-10-2017	All
E	Added System Block Diagram Added Specifications Updated Responsibilities Updated Timeline	12-14-2017	All

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1. Introduction

There is a market for optics to be used in assembly lines and other inspection systems for quality assurance that can adapt to defocus. Navitar is designing such a system that makes use of plenoptic imaging. With an optical system design done by a previous senior team, our team is looking to characterize the limits of this system, and the methodology of image reconstruction.

Statement:

The Plenoptic Imaging for Industrial Application is a senior design driven product. As such its design inputs are derived from our interactions with our project customers, Ian Wallhead and Russ Hudyma for Navitar, and our advisor, Dr. Scott Carney.

Vision:

To present a trade study of a plenoptic system with regard to microlens dimensions, sensor type and image space f/#, and to provide the image reconstruction tools to implement Navitar's plenoptic lens system.

2. Environment

As our final products are a trade study and the tools used, the environment is limited to the simulation work done in the computer and the tools written for interfacing with the simulations. These tools will be written in MATLAB and designed to interface with the pixel data files to be exported from Zemax.

3. Regulatory Issues

Since we will only perform lab work given additional time, the regulatory requirements have not been decided yet.

4. Fitness for Use

4.1 Fitness for Use

The case study will:

- Determine the viability of the application of plenoptic technology to Navitar's inspection lenses.
- Determine optimum plenoptic design parameter
- Provide meaningful data on how the micro-lens dimensions effect the system
- Provide meaningful data on how the image space f/# dimensions effect the system
- Provide recommendations for sensors and their integration into the system

The tools will:

- Interface with the pixel data files to be exported from Zemax
- Provide post processing functions that will reconstruct the plenoptic images
- Provide information on the limitations and effects of this process
- Have a run time that works with an assembly line application
- Pursue the three main approaches for designing the tools and provide details on the suitability of each
    1) Use a comparison method of determining how out of focus an image is by the comparison to a stored in-focus image
    2) Use epipolar images to create a 3-dimentional field map to determine the amount of defocus
    3) Use a sampling method of determining how many micro-lens arrays out of a set of central pixels should be reconstructed from

Given additional time and recourses we will:

- Create a GUI to interface between the tools and the provided images
- Work in the lab with provided equipment demonstrating our research

4.2 Specifications

The post-processing tools	
Programming Language	Matlab (version later than R2016a)
Input	Pixel data file (.txt) exported from Zemax
Output	Reconstructed images (.jpg)

4.3 Desirables

The product to be developed in this project will finally be used as an imaging system for industrial inspection, such as nano-circuits inspection. Therefore, although our primary objective is to develop a reconstruction tool to reconstruct the image generated by the plenoptic system, we should also try to adapt our tools into industrial circumstances. If time permits, we should develop a tool that:

- Is compatible with current imaging sensors for data collection
- Is able to reconstruct out-of-focus images with a relatively large range of out of focus distance, that it can be used to inspect various industrial products
- Can give real-time response for determining the best focus position that is compatible to industrial assembly lines
- Has minimum amount of resolution loss

5. Project Scope

5.1 System Block Diagram

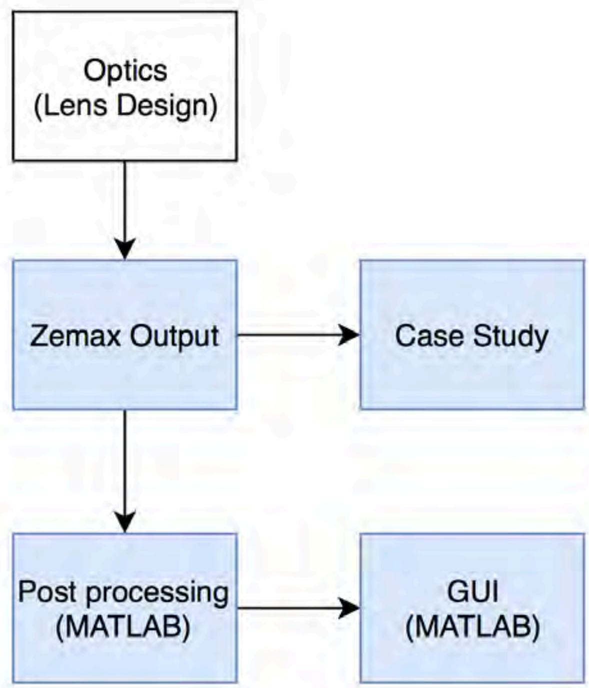


Figure 1: System Block Diagram. Shaded Blue Boxes are our responsibilities.

5.2 We Are Responsible for:

- Generating un-reconstructed image formed by the plenoptic lens using Zemax simulation
- Studying on the un-reconstructed image of different out of focus distances
- Reconstructing the image using MATLAB
- Developing a GUI for future use
- Developing a method to determine the best focus position

5.3 We Are Not Responsible for:

- Applying the research to alter the design of the system

6. Design Options

As the main task is to characterize the system, the main design portion is the design of the reconstruction algorithm. The difficulty in the reconstruction process is determining the amount of defocus in the system, as a simple iterative program can then be used to reconstruct using micro lens image properties. To determine the defocus several methods could be used, possibly a combination of tests could be used.

One possible method is a calibration test, as this could be used for an assembly line in which an in focus picture of the object is provided, then a comparison could be used to determine the amount of defocus. According to our customer a calibration test would be needed, but it needs to be a fallback solution to the standard due to implementation issues.

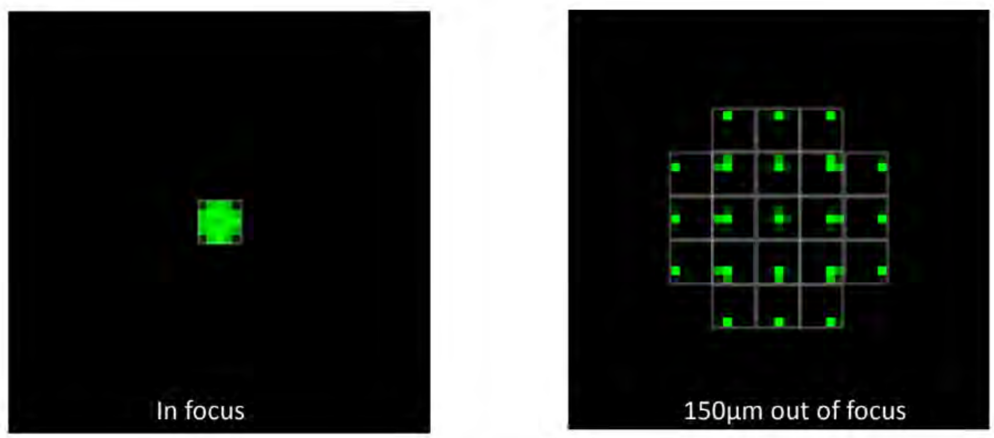
Another method is that if a stage is built into the product, a small calibration spot could be included to compare the focus of the known distance height to the object height to determine the defocus using epipolar imaging. Our customer believes that this would be useful especially for objects with height, as epipolar images are mainly used to create a 3D map, and could be used in conjunction with the third method.

The last method is to determine the amount of defocus in terms of micro lens arrays. This could be done by iteratively reconstructing the image guessing at the amount of defocus, and then determining which is the best picture. Our customer is concerned with the run time of the reconstruction, and asked us to look into potential methods to reduce it. This method is the one our customer was most interested in pursuing.

7. Preliminary Results

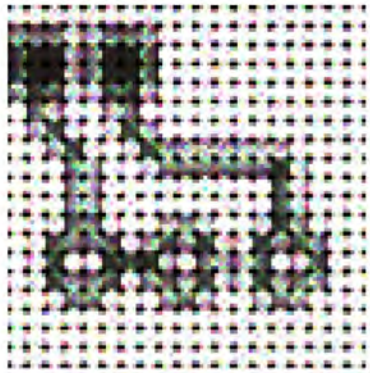
7.1 Reproduce the image reconstruction using the method from last year's group

7.1.1 Microlens image



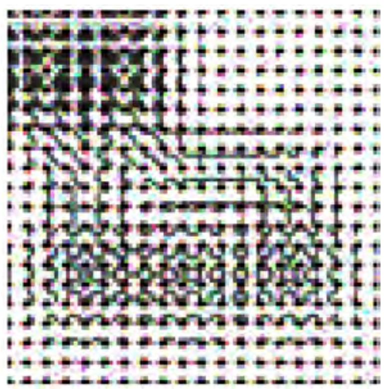
150um is equivalent to 1 micro lens image out of focus. In the reconstructed image the pixels next to the center pixels given 1 micro lens image of defocus will be in the next micro lens array and one pixel over.

7.1.2 Reconstructed images



Original image at 0 defocus

Reconstructed image at 0 defocus



Original image at 150um Defocus

Reconstructed image at 150um defocus

Note: Original images (left column) are from Zemax simulations, reconstructed images (right column) are the post-processed images using last year's method.

7.1.3 Problems with last year's method

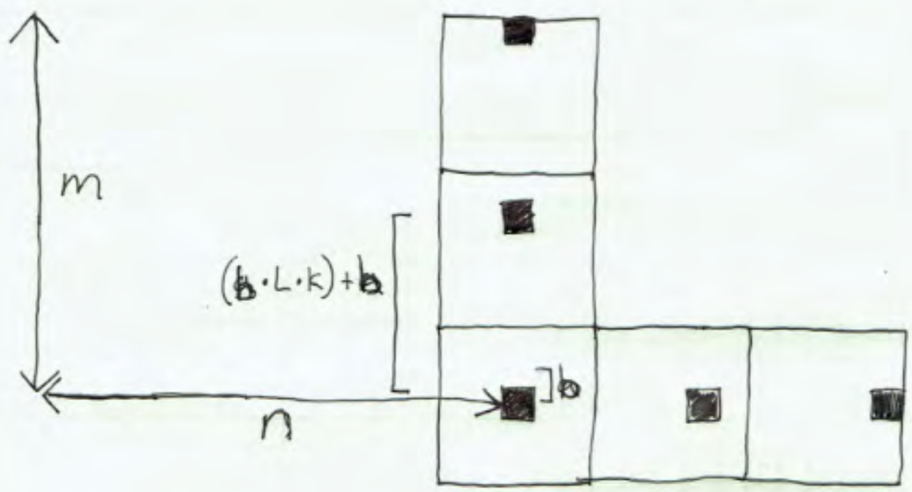
- Only provided proof of concept at certain known defocus
- Loss of resolution – 25 pixels to 1 pixel
- Loss of Contrast – null spaces

7.2 New idea this year

7.2.1 Image Reconstruction Concept Generalization

L = the number of pixels in a row in the micro lens image

k = the integer value for the amount of defocus given in micro lens images



Given array of normalized image values

For reconstruction of a single microlens image with coordinates (n,m) for its center pixel, obtain the value of pixels $(n-\lfloor \frac{L}{2} \rfloor, Yval)$ to $(n+\lfloor \frac{L}{2} \rfloor, Yval)$ for Y values $(m-\lfloor \frac{L}{2} \rfloor)$ to $(m+\lfloor \frac{L}{2} \rfloor)$

the value of a pixel im the micro lens image with pixel location $(n+a, m+b)$ can be found in the image at location

$$(n+(a\cdot L\cdot k)+a,\ m+(b\cdot L\cdot k)+b)$$

7.2.2 Reconstruction Algorithm Pseudo Code

Reconstruct Image

Arguments:

L the number of pixels in a micro lens image

K the defocus given in micro lens images (can be negative)

I the array of doubles giving the normalized value of the pixel

Code:

```
Create a new double array J with width and height of I
 For every center pixel in I
        J = Reconstruct Micro Lens Image (N, M, L, K, I, J)
 Print J
```

Reconstruct Micro Lens Image

Arguments:

N the X coordinate of the center pixel

M the Y coordinate of the center pixel

L the number of pixels in a micro lens image

K the defocus given in micro lens images (can be negative)

I the array of doubles giving the normalized value of the pixel

J the array of doubles with the reconstructed values of pixels

Code:

```
For each row in the micro lens image (M – L/2) to (M + L/2)
        For each column in the micro lens image (N – L/2) to (N + L/2)
                Int A = (Current X coor - N)
                Int B = (Current Y coor - M)
```

Set J (current pixel) = Get PixelValue (A, B, N, M, L, K, I)

Return J

Get Pixel Value

Arguments:

A the X coordinate difference from current pixel to the center pixel

B the Y coordinate difference from current pixel to the center pixel

N the X coordinate of the center pixel

M the Y coordinate of the center pixel

L the number of pixels in a micro lens image

K the defocus given in micro lens images (can be negative)

I the array of doubles giving the normalized value of the pixel

Code:

Return I [N + (A * L * K) + A] [M + (B * L * K) + B]

7.2.3 Current MATLAB Code

```
K = 3; %This is how many microlens array images out we look for the
first pixel from the center pixel
%There will be 2K + 1 images created
L = 5; %This is how many pixels in a row/column in a microlens image

%Taken from the original MATLAB code
PixelWide = 4096;
PixelHeight = 2160;

%change this at some point to be flexible by L
CenterRefocusWidth = 20;
CenterRefocusHeight = 20;

%The lop left center-pixel to be reconstructed
TopLeftX = 48-(CenterRefocusWidth/2);
TopLeftY = 48-(CenterRefocusHeight/2);

load book_150.txt;
I = book_150;
figure; hold on
imshow(I,'InitialMagnification',400);
title('Original image from Zemax (+150um)');
print('Original image from Zemax (+150um)', '-dpng');
hold off

step = 1;
for k = -1*K:step:K
%From -K to K reconstuct an image assuming a defocus of k
    %iterate through all the area to be reconstructed
    for n = TopLeftX:L:(TopLeftX + CenterRefocusWidth)
        for m = TopLeftY:L:(TopLeftY + CenterRefocusHeight)
          %iterateThrough the microlens array with center pixel at (n,m)
            for a = -1 * floor(L/2):step:floor(L/2)
                for b = -1 * floor(L/2):step:floor(L/2)
                    temp1 = n + (a*L*K) + a;
                    temp2 = m + (b*L*K) + b;
                    [x,y] = size(I);
                    if (temp1 <= x && temp2 <= y)
                        J(n + a, m + b) = I(temp1, temp2);
                    end
                end
            end
        end
    end
    figure; hold on
    [jx, jy] = size(J);
    imshow(J(TopLeftX-floor(L/2) : jx, TopLeftY-floor(L/2) :
jy),'InitialMagnification',400);
    title(['k= ', num2str(k)]);
    print(['k=', num2str(k)], '-dpng');
    hold off
end
```

7.2.4 Current Problems

- Due to the run-time constraint, we only reconstruct center until k is determined, which might result in potential imprecision.
- The problems of loss of contrast and loss of resolution still exist. However, such loss might be unavoidable, and more research is needed.
- This method does not work for non-integer k values.

8. Resources Needed

The following software will be used in the design process:

- ZEMAX for analyzing the lens system and generating the pixel data files
- MATLAB for implementing the post-processing system

9. Timeline

Fall Semester	
Oct 12th	Assigned project
By Oct 18th	• Started study on research papers and dissertation sent from customer • First customer meeting to discuss timelines and goals for the project • Obtained Zemax lens files, original image files and Matlab reconstruction tools
By Nov 1st	• Started Initial Reconstruction analysis • Identify product specifications and project expectations
By Nov 15th	• Successful Reconstruction of images at in-focus and 150um out of focus positions (Recreation of last year's result)
By Nov 28th	• Revised Matlab reconstruction codes and successfully reconstructed of image at 6 different known out of focus position ranged from -250um to 300um • Designed new reconstruction algorithm for arbitrary out of focus distances • First faculty advisor meeting • Started research on computation photography with plenoptic system using Fourier imaging methods
By Dec 6th	• Developed and tested prototype reconstruction algorithm pseudo code
By Dec 11th	• Clean up and conclude preliminary results • Final PRD presentation and review for this semester
Spring Semester	
January	• Rochester Navitar Tour
By Feb 2nd	• Reconstruction function updates
By Feb 16th	• Reconstruction Function Improvements – contrast/non integer K
By March 2nd	• Characterization of System with Function
By March 16th	• Sensitivity analysis of Defocus
By March 30th	• Create GUI interface
By April 27th	• Project wrap up/Create Poster Presentation

10. References

[1] Kim, Jonghyun, et al. "Real-time integral imaging system for light field microscopy." Optics express 22.9 (2014): 10210-10220.

[2] Ng, Ren. Digital light field photography. California: stanford university, 2006.

[3] Lam, Edmund Y. "Computational photography with plenoptic camera and light field capture: tutorial." JOSA A 32.11 (2015): 2021-2032.

[4] Presentation from our customer, Navitar Inc.