3D Plenoptic Microscope System

Product Requirement Document

3D Team: Nightingale

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Revision History:

   - Specifications for System
   - Vision
   - System Layout and Design Appearance Expectation
   - Update Specifications for Objective
   - Environmental Requirements
   - Timeline
   - Responsibilities
   - Appendixes
   - Finalize specification table
   - Finish appendix
   - Final revisions and editing
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**Introduction:**

Light-field (plenoptic) cameras can capture both spatial and angular information, which can be reconstructed to form an image with depth information using additional software. Since a single capture is sufficient, a plenoptic camera requires less time to capture 3D images than a traditional, manual approach. This makes a plenoptic camera suitable for industrial inspection.

This senior design project is a collaboration with Navitar, Inc., a manufacturer of optical systems who focuses on designing, developing, manufacturing and distributing precision optical solutions across the globe.

**Vision:**

Project Nightingale is an apochromatic, plenoptic microscope with high-resolution 3D reconstruction capabilities and a long working distance. One application of this plenoptic camera is the inspection of microelectronic components on assembly lines. To serve this purpose, this plenoptic system will consist of five components: an objective lens, a tube lens, a relay stage, a micro-lens array, and a sensor, as illustrated in Figure 4.

**Operating Environment:**

As an industrial inspection device, the system needs to survive in -40 °C to 70 °C and operate at room temperature with no significant change in performance across normal room temperatures.
Specifications:

A. System Specifications Table:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnification</strong></td>
<td>1x or 2x</td>
</tr>
<tr>
<td><strong>Wavelength</strong></td>
<td>450nm, 550nm, 650nm</td>
</tr>
<tr>
<td><strong>Working distance</strong></td>
<td>90 mm</td>
</tr>
<tr>
<td><strong>Field of View</strong></td>
<td>8mm diagonal object space</td>
</tr>
<tr>
<td><strong>Total Length</strong></td>
<td>415 mm</td>
</tr>
<tr>
<td><strong>Objective F/#</strong></td>
<td>10 (1x)</td>
</tr>
<tr>
<td><strong>(2x)</strong></td>
<td>5 (2x)</td>
</tr>
<tr>
<td><strong>Imager Format</strong></td>
<td>1” (4K compatible)</td>
</tr>
<tr>
<td><strong>Number of pixels</strong></td>
<td>4096 x 2160</td>
</tr>
<tr>
<td><strong>Sensor size</strong></td>
<td>14.13 x 7.51 mm</td>
</tr>
<tr>
<td><strong>Pixel size</strong></td>
<td>3.45 µm</td>
</tr>
<tr>
<td><strong>Image Circle (nominal)</strong></td>
<td>16 mm diameter</td>
</tr>
<tr>
<td><strong>Distortion</strong></td>
<td>&lt;0.25%</td>
</tr>
<tr>
<td><strong>Relative Illumination</strong></td>
<td>&gt;85%</td>
</tr>
<tr>
<td><strong>Design MTF</strong></td>
<td>&gt;40% across field at 72.5 lp/mm (1x)</td>
</tr>
<tr>
<td><strong>(2x)</strong></td>
<td>or at 145 lp/mm</td>
</tr>
<tr>
<td><strong>Telecentricity</strong></td>
<td>Yes, in sensor space</td>
</tr>
<tr>
<td><strong>IR Filter</strong></td>
<td>Included</td>
</tr>
<tr>
<td><strong>Plenoptic Type</strong></td>
<td>Plenoptic 1.0 (pupil relay type)</td>
</tr>
<tr>
<td><strong>Plenoptic Micro Lens Array</strong></td>
<td>Details in Following Content</td>
</tr>
<tr>
<td><strong>Other Requirements</strong></td>
<td>1. 2 surfaces ghost image analysis. No ghost images on image plane</td>
</tr>
<tr>
<td><strong>(2)</strong></td>
<td>2. Aperture locates 4mm after objective lens</td>
</tr>
</tbody>
</table>
B. Objective Lens Specifications Table:

<table>
<thead>
<tr>
<th>Maximum (Preferably) Incident Angle</th>
<th>38° (30°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>For 1x Configuration</td>
<td></td>
</tr>
<tr>
<td>Object Maximum Space Field</td>
<td>8mm</td>
</tr>
<tr>
<td>Object Space Aperture</td>
<td>f/10</td>
</tr>
<tr>
<td>Object Space Resolution</td>
<td>72.5 lp/mm</td>
</tr>
<tr>
<td>For 2x Configuration</td>
<td></td>
</tr>
<tr>
<td>Object Maximum Space Field</td>
<td>4mm</td>
</tr>
<tr>
<td>Object Space Aperture</td>
<td>f/5</td>
</tr>
<tr>
<td>Object Space Resolution</td>
<td>145 lp/mm</td>
</tr>
</tbody>
</table>

C. Afocal Relay Specification Table:

<table>
<thead>
<tr>
<th>Overall Length</th>
<th>100mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnification</td>
<td>1x</td>
</tr>
</tbody>
</table>

D. Tube Lens Requirements:

The tube lens must be an off the shelf doublet from Edmund Optics or another appropriate vendor. The effective focal length of the tube lens is dependent on the system magnification and the effective focal length of the objective lens. If the system magnification is 1x, the focal length of the tube lens will be the same as the focal length of the objective, and if the system magnification is 2x, the focal length of the tube lens will be twice the focal length of the objective.
E. Micro Lens Array Requirements:

The micro lens array is required to be an off the shelf product from Edmund Optics or another appropriate vendor.

Figure 1: An example of a micro lens array from Edmund Optics¹.

F. Potential Camera Selection:

The camera is required to be an off the shelf product from Pixelink with a Sony CMOS IMX254 or IMX255 sensor package.

Figure 2: An example of a camera from Pixelink²


² Source: http://www.pixelink.com/
Design Responsibilities:

We are responsible for:

1. Designing the lens system, as suggested by customer, consisting of an objective, a relay stage, and a tube lens.
   - Infinity corrected, apochromatic microscope objective with a working distance of 90mm.
   - A 1x afocal stage of 75-100mm length. This could be replaced with a zoom stage in future upgrades.
   - A telecentric tube lens system of approx. 200mm focal length. The actual focal length will need to be determined to achieve 2x magnification.
   - The above 3 sub-systems together form a stand-alone microscope inspection system.

2. Designing the plenoptical system, including selecting a suitable micro lens array and camera.

Desirable:

1. Testing the prototype
2. Generating 3D images using prototype
3. Analyzing the noise propagation through the system onto the reconstructed images

Not Responsible for:

1. Satisfying any mechanical design requirement. e.g. (3 ft. drop test)
2. Prototyping, including system alignment, enclosure design, system assembly etc.
3. Survival of humidity ranging from 0 to 100%
System Layout:

**Figure 3. System Illustration.** A current product that has a similar layout and dimensions as the product we are designing.

**Figure 4. Plenoptic System Sketch.**
Timeline:

Fall Semester:

December:


Start preliminary design for objective lens, tube lens and relay stage.

Spring Semester:

January:

Continue working on preliminary design:

- Determine whether the system functions optimally at 1x or 2x.
- Work on reducing color aberrations.
- Put the entire system together and begin to optimize.

February:

Optimize the optical system.

Study the micro-lens array.

March:

Choose the proper micro-lens array.

Optimize the design of system as a whole with: objective lens, tube lens, relay stage, micro-lens array and sensor.

Tolerance and possible redesign if necessary.

April:

Prepare for final presentation for the class and to the customer.

Note:

If our team can finish the design of the system ahead of schedule, we will send the design to Navitar’s rapid prototyping team, who will build the system in 2-5 weeks. During that time, we will work on designing an experiment to conduct with the finished product.
Appendix:

A. Lytro: A Study

Abstract
System designers, like Newton, stand on the shoulders of giants. As we were completing our designs for Nightingale objective and relay, we began to search for design references for the light-field part. Thanks to a generous loan of a Lytro from Professor Fienup, we decided to investigate the consumer light-field camera. We set up several experiments to evaluate its performance and read a few papers and patents related to its design. This report documents our findings with Lytro and suggests some possible starting points for our micro lens array design.

Background
Lytro is a consumer light-field camera that grew from Ren Ng’s doctoral dissertation. We tested the first generation version released in 2012.

Figure A-1: Lytro Camera (First Generation)
 Specifications

Table A-1: Selected specifications of Lytro First Generation.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal Length</td>
<td>43 mm -- 344 mm</td>
</tr>
<tr>
<td>Zoom</td>
<td>8x optical</td>
</tr>
<tr>
<td>Aperture</td>
<td>Constant f/2.0</td>
</tr>
<tr>
<td>Sensor Type</td>
<td>CMOS</td>
</tr>
<tr>
<td>Light Field Resolution</td>
<td>11 megaray</td>
</tr>
<tr>
<td>Active Area</td>
<td>4.6 mm x 4.6 mm</td>
</tr>
<tr>
<td>2D Image Resolution</td>
<td>1080 px x 1080 px</td>
</tr>
</tbody>
</table>

Tests

Table A-2: The distances of the USAF-1951 targets. Target -2,1 is 14 mm wide.

<table>
<thead>
<tr>
<th>Target</th>
<th>Distance (m)</th>
<th>Smallest Resolvable Target</th>
<th>Spatial Resolution (lp/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.60</td>
<td>0, 1</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>0.80</td>
<td>-1, 5</td>
<td>0.57</td>
</tr>
<tr>
<td>3</td>
<td>1.06</td>
<td>-1, 4</td>
<td>0.51</td>
</tr>
<tr>
<td>4</td>
<td>1.34</td>
<td>-1, 3</td>
<td>0.45</td>
</tr>
</tbody>
</table>

3Source: https://support.lytro.com/hc/en-us/articles/200863400
Figure A-2: Four 2D images generated from the light-field image.
Each 2D image is focused on one of the four targets. The generated images simulate an aperture of f/2.0.
We tested the camera by capturing a scene with four USAF-1951 targets at various distances. With the 3D light-field image, the Lytro software generated five 2D images. Four of them were generated under f/2.0 configuration, each with focus on one target. The fifth image was generated under f/16.0.

The strength of Lytro appears to be its ability to generate images with various focuses with only one capture. This ability significantly reduces the time it takes to capture the scene. In an industrial setting, a faster camera with depth-mapping ability may increase its productivity.
B. Early Stage Design

Objective Design - F/10, System Mag: 1x

This is an example of a preliminary objective design for a system with a system magnification of 1x. The design meets the image quality requirements defined in the specification section of this document.
Objective Design - F/5, System mag: 2x

This is an example of a preliminary objective design for a system with a system magnification of 2x. The design nearly meets the image quality requirements defined in the specification section of this document.