**Zoom Lens Specification**

This zoom lens is intended for use with a consumer-market digital camera. In this case, a large zoom is desired and will image to a 4 Megapixel camera chip. Due to market demand, this lens system should be designed with size and weight constraints to remain easily portable. Specific design criteria are as follows:

**Lens System:**

High power magnification – 8x or above

Compact design – appropriate for a pocket-sized camera, with capability to compress to 1-2”

High resolution – compatible with current, as well as future, small pixel-sized cameras (several micron pixel pitch)

High throughput – minimal loss for low-light conditions

High Image Quality – Aberrations (spherical, chromic…) must be minimized

**Camera Chip:**

4 Megapixel: 2000 x 2000 pixels

Pixel pitch = 10um

Chip width = 20mm
Possible Approaches and Design Selection

To better grasp the complexity of this problem, the design was first approached with the simplest of system designs. Paraxial ray trace diagrams were quickly constructed for several general lens combinations. The main specification to satisfy at this phase was the ability to adjust the magnification of an object at a fixed distance, or zoom. Image location as well as the required travel for the lenses was also considered.

The first system considered was the simplest case, that of two positive lenses. This system allows for magnification by adjusting the distance between the two lenses, however is limited by the available object planes to which it can focus. Several general cases were drawn and may be found in the following figure.

Figure 1: Two Positive Lenses
The next logical choice (for a new, inexperienced designer) was to combine a negative with a positive lens. Both configurations, negative or positive lens first, were briefly examined. In the case where the negative lens is first in the chain, magnification is achieved but zoom is not obvious. These attempts are pictured below.

![Figure 2: Negative and Positive Lens](image)

When the lenses are reversed, however, the system begins to approach correct functionality. This particular configuration is a simple telephoto lens system. This system provides zoom, but creates a virtual image. It is clear that additional lenses must be added.
Next, a third lens was added to the telephoto system. A positive lens was chosen to focus the diverging rays back towards the optical axis so that a real image would be formed. This configuration is known as a Cooke triplet. Immediately, an interesting property of this system was observed. For collimated input, such as light from distant objects, this triplet system can produce collimated output. By then adjusting the distances between the lenses, the output may be expanded or reduced. This creates the zoom action desired for the design. These schematics are all pictured below.
Now that the correct zoom behavior is modeled, a real image must be formed. By adding a forth (positive) lens to the output of the system, the rays will bend towards the optical axis and a real image will be formed. This approach was chosen for the zoom lens design.
**Paraxial Design**

For this design process, y-u ray tracing was used to learn about the system and to place the lenses and decide prescriptions. A simple program was written that followed several object rays, including the paraxial marginal ray (PMR) and chief ray (PPR), through the system while the lens powers and locations were adjusted.

Several constraints were known from the previous paraxial test designs. The first such constraint is that the total distance between lens 1 (L1) and L3 needed to be less than the focal lengths of the lenses. Additionally, L1 and L3 are chosen to have the same power to create a symmetry that seems desirable. Moreover, these prescriptions should be strong as a shorter overall system length is desirable. Once these constraints were in place, an object was chosen to further limit variables.

A 400mm high object was placed 1200mm in front of the system so that it was close enough to provide significant incoming ray angles. This seemed a reasonable approximation of a human head in a typical portrait scenario. This object choice also facilitated zoom design as it could be magnified and imaged to meet the design specifications. Additionally, maximum image size is limited to a total height/width of 20mm due to the size of the camera. Now that several variables are under constraint, the design could begin.

The lens prescriptions and locations are the only adjustable variables remaining. At this point, the Newport lens catalog was reviewed so that the design would be limited to mass-produced lenses. Referencing the catalog forced a limitation of the lens powers
to increments in available focal length and diameter combinations. Once potential lens specifications were known, the system was assembled.

With thin lenses in the system, some trends could be observed. First, in some cases by shortening the distance between L1 and L3, the zoom reduced linearly. Additionally, by adjusting the distance between L1 and L2 or L2 and L3, the magnification increases and decreases respectively. Other effective means to alter the magnification are to alter the power of L2 or the imaging lens, L4. With this knowledge, the system could be separated in function and designed to reach the desired magnification and zoom. This design requires each lens to move position to both acquire the desired magnification and to image onto the camera. This motion is pictured in Figure 5 for the case of collimated input.

![Figure 5: Triplet Motion](image)

**Figure 5: Triplet Motion**
The imaging lens, L4, is absent from the above diagram. In the case of collimated light, this imaging lens can remain stationary with respect to the image plane. For the camera lens, however, the incident light will never be perfectly collimated. Thus, the distance between the Cooke triplet and L4, as well as L4 and the image plane will remain free variables.

The maximum motion of the imaging lens was considered and an attempt to minimize its motion was made. Initially, the design did not quite accommodate available lenses. The distances between the lenses were not adequate once thick lenses with real curvatures were inserted. This problem was corrected for the layouts found below. The following schematics show the two end points (minimum and maximum zoom) of the system.
Figure 6: Paraxial Thin Lens Layout for Minimum Zoom Condition
Figure 7: Paraxial Thin Lens Layout for Maximum Zoom Condition
Gaussian Design

For a mass produced consumable such as this zoom lens, cost is of great concern. In order then to reduce the cost of this system, inexpensive, readily available lenses were desired. To meet this need, BK 7 glass lenses in standard prescriptions were chosen from the Newport Corporation’s catalog. These lenses range in price, depending on the desired coating, from $29-$104 a piece. Considering the use, a broadband visible antireflection coating (Newport #AR.14) is appropriate. This AR coating choice pushes to total lens cost of the system to $297. This price would be greatly reduced if large quantities were needed for production. The following table displays the necessary design information for each lens.

<table>
<thead>
<tr>
<th>Position</th>
<th>Model (Newport)</th>
<th>Diameter (mm)</th>
<th>EFL (mm)</th>
<th>f#</th>
<th>BFL,FFL (mm)</th>
<th>P1 (mm)</th>
<th>P2 (mm)</th>
<th>Te (mm)</th>
<th>R (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>KBX142</td>
<td>50.8</td>
<td>50.2</td>
<td>0.9</td>
<td>44.13</td>
<td>6.06</td>
<td>-6.06</td>
<td>17.277</td>
<td>48.756</td>
</tr>
<tr>
<td>L2</td>
<td>KBC028</td>
<td>12.7</td>
<td>-12.5</td>
<td>-0.9</td>
<td>-13.29</td>
<td>0.79</td>
<td>-0.79</td>
<td>5.07</td>
<td>-13.333</td>
</tr>
<tr>
<td>L3</td>
<td>KBX142</td>
<td>50.8</td>
<td>50.2</td>
<td>0.9</td>
<td>44.13</td>
<td>6.06</td>
<td>-6.06</td>
<td>17.277</td>
<td>48.756</td>
</tr>
<tr>
<td>L4</td>
<td>KBX154</td>
<td>50.8</td>
<td>100</td>
<td>1.9</td>
<td>96.83</td>
<td>3.16</td>
<td>-3.16</td>
<td>9.444</td>
<td>101.73</td>
</tr>
</tbody>
</table>

**Figure 8: Bi-Convex Lens Schematic**  
**Figure 9: Bi-Concave Lens Schematic**

The following diagrams expand the thin lens designs by including these real lenses.
Figure 10: Paraxial Thick Lens Layout for Minimum Zoom Condition
Figure 11: Paraxial Thick Lens Layout for Maximum Zoom Condition
System Analysis and Conclusion

Finally, the system was analyzed at both extreme cases for performance. Throughout the design process, an intermediate zoom condition was checked for reasonable behavior. For simplicity of analysis, however, only the aforementioned zoom end points were closely explored to better understand the limits of this design.

Power

The initial design criteria called for 8x or higher zoom capabilities. The minimum and maximum zoom powers were thus calculated and compared. Using the expressions for system power,

\[ K = \frac{n u_\infty}{h_1} \]  

\[ F = \frac{1}{K} \]  

\( F_{\text{min}} \) is found to be 27.3mm while \( F_{\text{max}} \) is 186.57mm. The ratio of these focal lengths yields a camera lens power of 6.8x. While impressive in comparison to typical digital cameras that advertise 3x zoom, this falls short of the desired specification. This discrepancy developed when the thin lens design was altered to accommodate thick lenses. The original thin lens design allowed for closer spacing of the lenses, and slightly higher powers resulted. Unfortunately, the lenses chosen are quite thick and the distances between the lenses were forced higher.

Furthermore, when compared to typical commercial zoom lenses, these focal lengths are larger by about a factor of three. This difference reflects the rather long
This system does not meet the desired length specification. After exploring the 4-lens system to great depths, it appears the only way to reduce the system length is to increase its complexity by adding more elements. Increasing the number of elements would also eliminate the need for such strong lenses (F/1 for L1-L3) and would improve aberrations.

**Principal Planes**

The principal planes were not specified in the design plan, but should be known for future design considerations. The equations for the principal planes from the last and first lenses respectively are found below.

\[
\delta' = -\frac{h_1 - h_k}{u_k}, u_k = 0 \quad (m) \quad (3)
\]

\[
\delta = -\frac{h_1 - h_k}{u}, u_k = 0 \quad (m) \quad (4)
\]

\(\delta'_{\text{min}} = -45.3\) mm from P of lens 4

\(\delta_{\text{min}} = 39.5\) mm from P’ of lens 1

\(\delta'_{\text{max}} = 131.3\) mm from P’ of lens 4

\(\delta_{\text{max}} = -169.4\) mm from P of lens 1

**Image**

The imaging metrics are of utmost importance for a camera lens. The following calculations explore some imaging parameters for the case of the object located at 1200mm.
Infinite Conjugate Condition: Minimum Zoom

\[ F / \# = \frac{F_{\text{system}}}{D_{\text{AS}}} \]
\[ F / \# = 1.7 \]

Finite Conjugate Condition: Maximum Zoom

\[ F / \#_{\text{object}} = \frac{f(1 - \frac{1}{M})}{D} = \frac{F_{\text{system}}(1 - \frac{1}{M_{\text{system}}})}{D_{\text{AS}}} \]
\[ F / \#_{\text{object}} = 14.9 \]
\[ F / \#_{\text{image}} = \frac{f(1 - M)}{D} = \frac{F_{\text{system}}(1 - M_{\text{system}})}{D_{\text{AS}}} \]
\[ F / \#_{\text{image}} = 3 \]

This is a large range of F/#s. The aperture range measures how much light is let into the camera when taking a photo. Low F/# settings are best for low light photography while higher F/#s provide a greater depth of field. This is apparent from the following calculations.

Depth of Focus at Image Plane

\[ \delta \xi = 2 \rho F / \# \]
\[ \delta z_{\text{min}} = 34 \text{ um} \]
\[ \delta z_{\text{max}} = 60 \text{ um} \]

This depth of focus was calculated for \( \rho \) equal to the pixel pitch of 10um. These field depths will require careful positioning of L4 to the camera. Additionally, the object space field depth was briefly explored. In the case of the 400mm high ‘head’ located 1.2m from the lens system, the object space depth of focus was found to be 140mm. This seems reasonable, as a face would easily remain in focus. Stopping down the aperture
stop would help increase this depth, but additional light throughput and camera sensitivity analysis would be necessary to find the limit.

Resolution

\[ r_0 = \frac{\lambda F}{\#} \]

\[ r_{0 \min} = 0.85 \text{ um} \]

\[ r_{0 \min} = 1.5 \text{ um} \]

These resolutions remain more than adequate as the camera becomes the limiting device. The camera has a maximum resolution of 10um, thus this lens system is at worst a factor of seven times more resolved. The resolution specification is thus met as this lens may accommodate higher resolution cameras for future products.

With analysis complete, several observations of the success of this design may be formed. First, the lens system performs fairly well despite missing the magnification specification. The lens still offers quite a large range of zoom, while creating resolvable images of which a clever lens mounting system could maintain focus. However, a glance at Figures 10 and 11 reveal the major flaw in the design: the lens is too large. This lens system grows to over 200mm in length and maintains a 50mm girth before lens mounts are included. This lens is simply too large for a practical consumer application. Furthermore, designing with F/1 lenses minimized these dimensions. These lenses are so strong that aberrations will dominate this system. For these reasons, one does not find such a lens in consumer cameras. Typical zoom lenses include 11, and sometimes up to 40, elements to create a compact design with minimal chromatic and spherical aberrations. The principles, however, remain much the same. The concept behind this design is
reasonable, but paraxial lens design quickly breaks down limiting the quality of design of such a system.