HW 1 – Marginal and chief rays, stop locations, and FOV.

A.S. is iris
F.S. and exit window are lens 2.
Angular and linear FOVs shown on plot.
HW 1 – yu trace, F, PP locs, pupil and window size and locs.

Entrance pupil is $\frac{1}{1/(1/10-1/60)} = 12 \text{ mm}$ (to right) of lens 1
Entrance pupil diameter = $(12/10)40 = 48 \text{ mm}$

Exit pupil is $\frac{1}{-1/(2/20-1/75)} = -15.79 \text{ mm}$ (to left) of lens 2
Exit pupil diameter = $\frac{1}{(-15.9/20)40} = 31.58 \text{ mm}$

Entrance window is $\frac{1}{1/(30-1/60)} = 60 \text{ mm}$ (to right) of lens 1
Entrance window diameter = $(60/30)40 = 80 \text{ mm}$
HW 1 = Demonstration that thick (Gaussian) system is equivalent to original. Original system and rays shown in blue, Gaussian system in red. Note that in all cases, blue and red rays overlap after final lens.
HW 2. First, paraxial design equations given constraints, making assumption that object is at front focal plane of lens 1:

NA derived from optical invariant:

\[
N_{spots} = \frac{5[\text{mm}]}{2 \times 10^{-3}[\text{mm}]} = 2500 = \frac{2}{0.5 \times 10^{-3}[\text{mm}]} \cdot H
\]

\[
H = 0.625[\text{mm}] = N_{obj} \cdot \overline{y}_0 = N_{obj} \cdot 2.5[\text{mm}]
\]

\[
N_{obj} = 0.25
\]

NA derived directly from resolution:

\[
N_{obj} = 1.22 \times 0.5[\mu\text{m}] / 2[\mu\text{m}] = 0.305
\]

The difference is 1.22 ~ 1.00 in the definition of H. I’ll use 0.3.

For telecentric imaging, the exit and entrance pupils are at infinity, implying that the AS is at the common focus between the lenses. In this geometry, \(M = -2 = f_2 / f_1\).

To avoid vignetting on the lenses (that is, so that neither lens is the field stop),

\[
D_1 = f_1 / F_{1\#} \geq h_{obj} + 2 f_1 N_{obj}
\]

\[
f_1 \geq \frac{h_{obj}}{1 - 2 \cdot 0.3} = \frac{5[\text{mm}]}{1 - 2 \cdot 0.3} = 12.5[\text{mm}]
\]

Solve for \(f_1\). Choose min val.

\[
f_2 \geq \frac{|M| \cdot h_{obj}}{1 - 2 \cdot 0.15} = \frac{10[\text{mm}]}{1 - 2 \cdot 0.15} = 14.29[\text{mm}] \rightarrow 25[\text{mm}]
\]

Can’t operate at F/1 and still get \(M = -2\).

\[
D_1 = 5[\text{mm}] + 2 \cdot 12.5[\text{mm}] \cdot 0.3 = 12.5[\text{mm}]
\]

Lens 1 at F/1

\[
D_2 = 10[\text{mm}] + 2 \cdot 25[\text{mm}] \cdot 0.15 = 17.5[\text{mm}]
\]

Lens 2 at F/1.43

Since both lenses not at F/1, we’re probably not at the minimum length. The remaining variable is the object position, which can probably be used to decrease length and push both lenses to F/1. This design has a total length of 75 mm.
HW 2. With object at distance -d before the first lens and image at distance d’ after second lens.

First, remember that the magnification of an afocal telescope does not depend on object distance and (thus) neither does the angular magnification. That’s handy. A quick calculation using the Newtonian form of the lens equation yields:

\[ d' - f_2 = \left( \frac{f_2}{f_1} \right)^2 (d + f_1) = M^2 (d + f_1) \]

Now calculating the lens filling with these new object and image distances:

\[ D_1 = \frac{f_1}{F_1} \geq h_{obj} + 2(-d)NA_{obj} \quad \text{Avoid vignetting on lens 1} \]

\[ f_1 \geq F_1 \left[ h_{obj} + 2(-d)NA_{obj} \right] \quad \text{Solve for focal length 1} \]

\[ f_2 \geq F_2 \left[ M h_{obj} + 2d'NA_{obj} \right] = F_2 \left[ M h_{obj} + 2F_1^2 (d + f_1)NA_{obj} \right] \]

\[ d = \frac{h_{obj}}{2NA_{obj}} - \frac{(F_2 - F_1)M + 2(F_1)(F_2)(M + 1)NA_{obj}}{\left( F_1 + F_2 \right)M + 2(F_1)(F_2)(M + 1)NA_{obj}} \quad \text{Solve for d} \]

\[ d = \frac{5}{2 \cdot 0.3} \left[ -\frac{2}{(2 + 1)0.3} + 1 \right]^{-1} = -6.82 \text{ [mm]} \quad \text{Plug in and find quantities} \]

\[ d' = 27.273 \text{ [mm]} \]

\[ f_1 = D_1 = 9.091 \text{ [mm]} \]

\[ f_2 = D_2 = 18.182 \text{ [mm]} \]

Now both lenses at F/1 and total system length is 61.37 mm, down from 75 mm before. This is the optimal design given the constraints.
HW 2. Ray sketches

First design:

\[ D_{\text{obj}} = 5 \quad f_{1} = 12.5 \quad D_{AS} = 7.73 \quad f_{2} = 25 \quad D_{\text{img}} = 10 \]
\[ D_{1} = 12.5 \quad D_{2} = 25 \]

Second design on same scale

\[ D_{\text{obj}} = 5 \quad f_{1} = 9.09 \quad D_{AS} = 2.8 \quad f_{2} = 18.18 \quad D_{\text{img}} = 10 \]
\[ D_{1} = 9.09 \quad D_{2} = 18.18 \]
Design project

Specs that might be relaxed: Length of the system, magnification, resolution, field, uniformity of resolution (vignetting).

Let’s start by keeping mag, resolution and field and just see what the F/# change does to the total system throw (-d + f₁ + f₂ + d’):

Answer: F/2 is painful, increasing the system throw by a factor of 100! Maybe we don’t want to go all the way to F2.

Let’s try keeping the F/2 lenses but see how relaxing the object size and resolution (NA) by up to a factor of 2 might help. When both object height and resolution are relaxed by a factor of 2, we get back to the same 61 mm throw. Note that throw grows linearly with field but superlinearly in NA.

With these two plots, we could explain to the customer that a) something has to be given up and b) what it might be.