High-speed Document Sensing and Imaging – Optical System

Xiao Zhang

Project advisor: Peter B. Catrysse

Introduction:

Digital imaging systems are everywhere these days. Digital cameras and camcorders are examples at the consumer end of the spectrum. The goal of these systems is to produce pleasing pictures. In industrial applications, large and complex pieces of equipment are increasingly equipped with digital imaging systems. In this case the system provides no longer pretty pictures rather it generates information about the status of the equipment.

We will explore and learn about high-speed document sensing and imaging for industrial applications in this project. In short-run digital printing presses for printing books and documents on-demand, there is a need for high-speed digital sensing to perform real-time misprint detection. Such a system should have all the familiar components of a digital camera system, i.e., imaging optics, solid-state image sensor, image processing software and hardware. The requirements, however, are different than those for consumer digital camera systems. We will evaluate different optical architectures that create an optical image of the printed pages in a high-speed document sensing system.
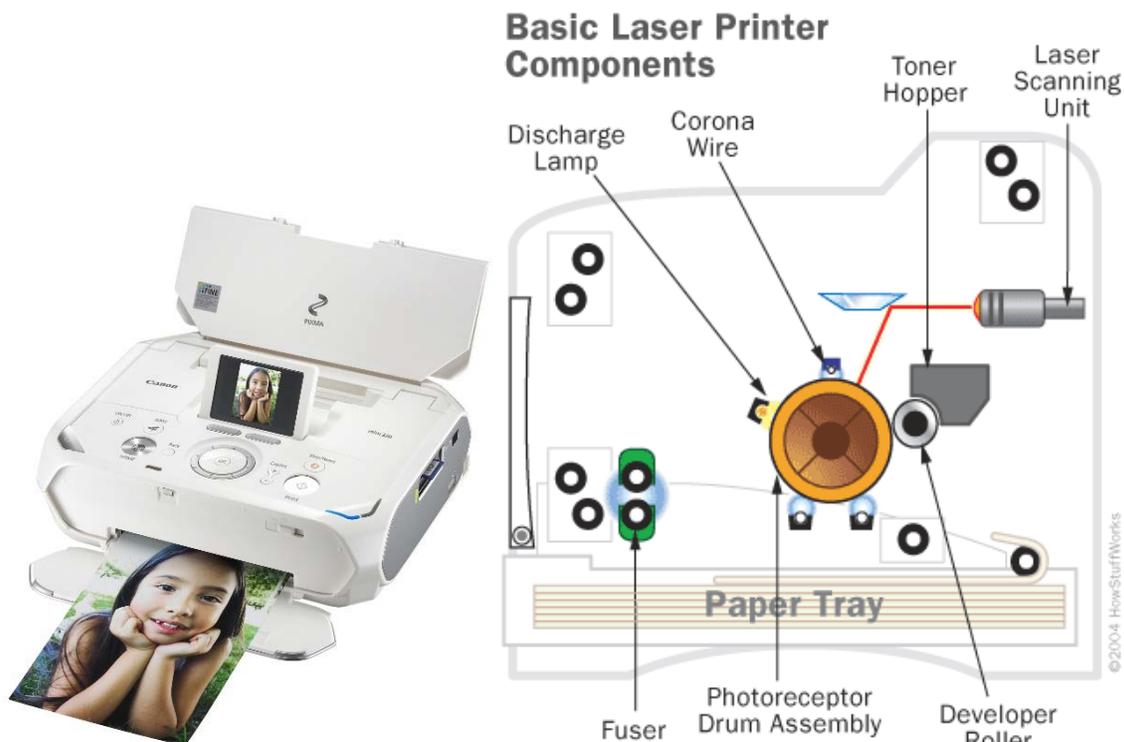

Fig 1. An illustration of today's printer (left fig. from [1], right fig. from [2])

The system that you will model and analyze in this project is a high-speed digital sensing solution for real-time misprint detection in short-run printing presses. There are different parts to such a system. The first part of the misprint detection solution is a high-speed, high-sensitivity optical detection system that measures the light reflected from the printed page under a known illuminant. The illumination and imaging optics are an important aspect of this first part.

The figure illustrates three different optical systems. The one on the left is a conventional imaging format in which the lens gathers light scattered from the surface. Many photons scattered from the surface are lost because they do not enter the lens aperture. The one on the right is near-contact. In this format the scattered light is nearly all collected by the detector and can produce an increase of 3 orders of magnitude in light collection efficiency. The difficulty on the right is finding a way to illuminate the surface and requires the same length of sensor as the web width. But with such a large efficiency, it may prove possible to illuminate through the print medium.
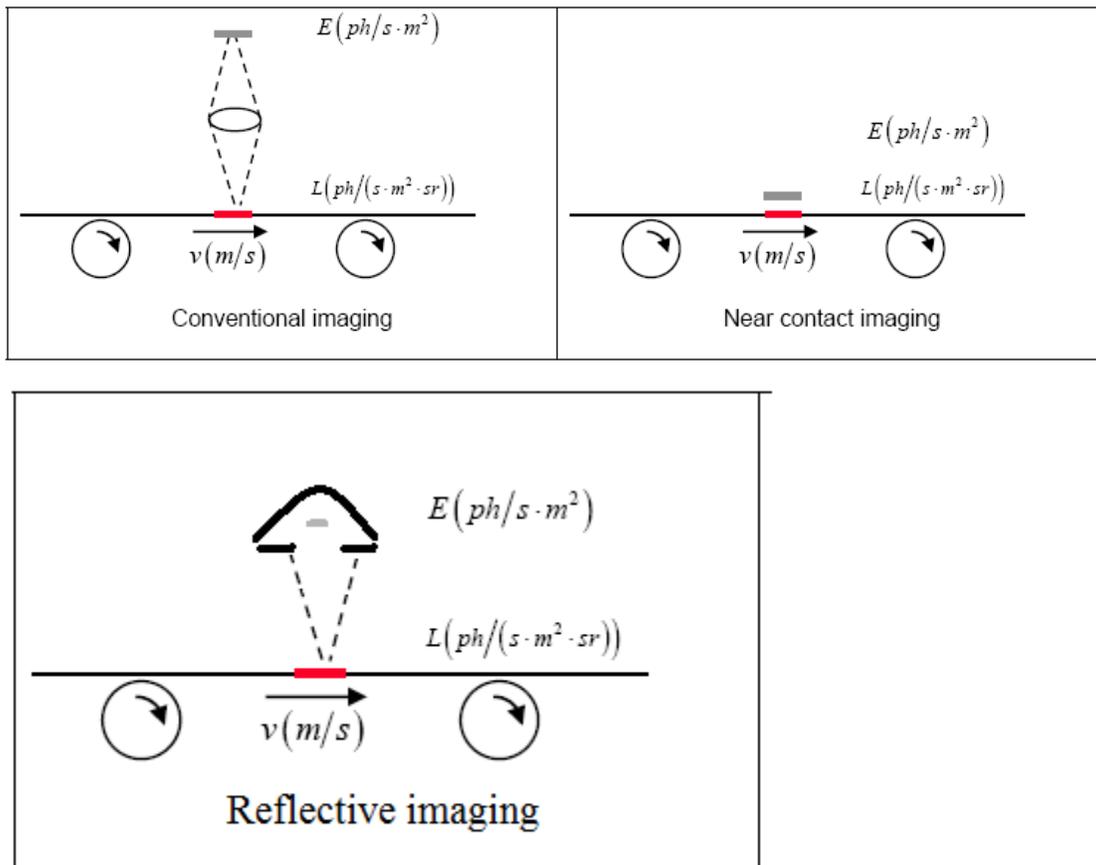

Fig 2. Different possible imaging optics architectures (Top two created by Peter for this project, bottom one created by myself).

Other architectures are possible as well. This system might lend itself very well to using highly efficient but FOV restricted reflective optics for both the illumination and the detection (see Patent Application US 2005/0099795). It is shown at the bottom of the above figure. Reflective optics with extremely low f-number (very high optical throughput) can be designed and might be applicable in this case.

Background Information

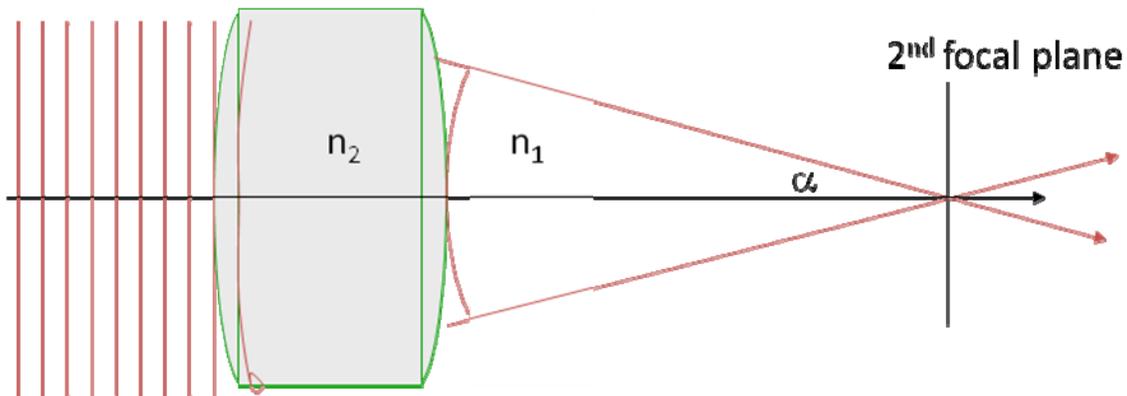## I. Numeric aperture and f-number

Fig 3. An illustration of f-number (from [4])

An aberration free lens will generate a spherical wave front whose radial extent is governed by the 'numerical aperture' $NA=n1\sin\alpha$. And we define f-number to be $f\#=1/(2NA)$. Following this definition, for far contact lens, $f\#\sim f/aperture$ diameter and for near contact system, f/0.5.

II. Refraction at a spherical glass surface

Note that the angle of deflection, $(\theta1-\theta2)$, is proportional to the radius. As $\theta1$ increases the first order approximation becomes more dubious and aberrations become significant and not all rays (for different $\theta1$) will cross the axis at the same point; this is spherical aberration. Correcting for spherical, and other, aberrations can be accomplished by incorporating many refracting surfaces.
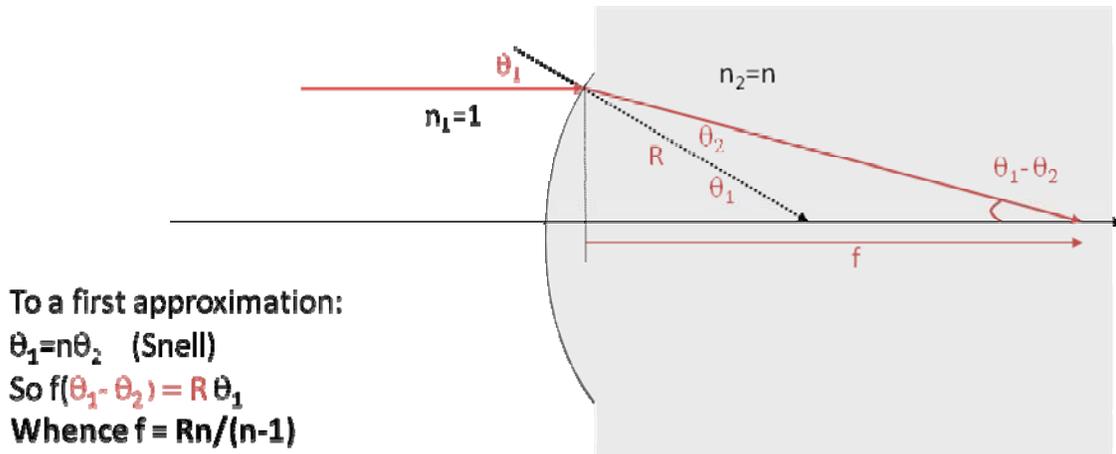
To a first approximation:
$\theta_1 = n\theta_2$ (Snell)
So $f(\theta_1 - \theta_2) = R\theta_1$
Whence $f = Rn/(n-1)$

Fig. 4 An illustration of refraction at a spherical glass surface with first order approximation (from [4])

III. Spherical aberration

Spherical aberration is due to nonlinear effect of Snell's law. There are longitudinal and transverse spherical aberrations, shown in the following figure. Spherical aberration is on-axis effect. LA (longitudinal spherical aberration) $\sim 1/(f\#)^2$, TA (transverse spherical aberration) $\sim 1/(f\#)^3$. These proportionalities also apply to reflective systems, just as all the other blurring effects below.
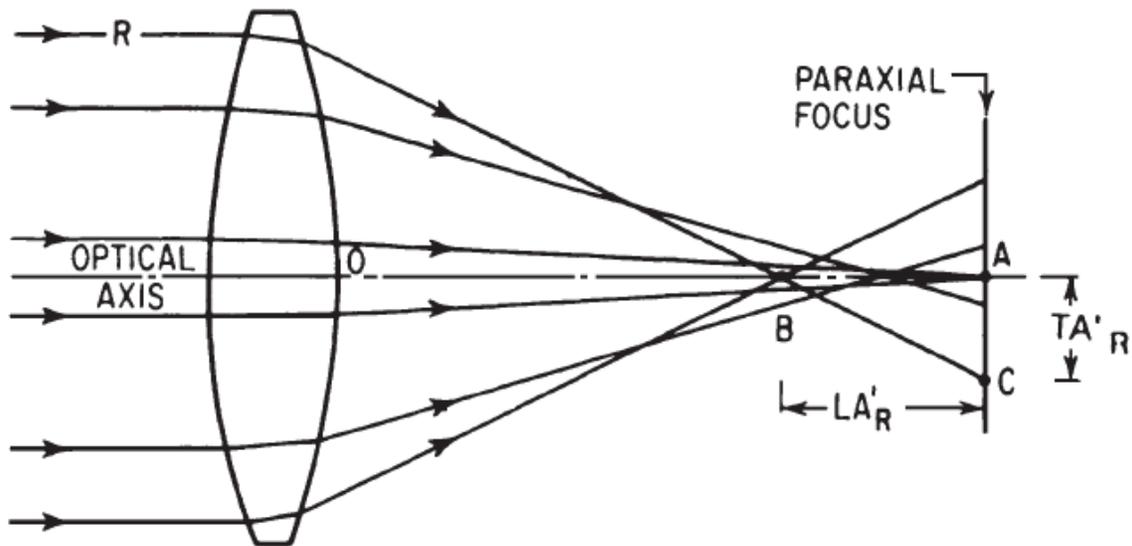
Fig. 5 A simple converging lens with under corrected spherical aberration. The rays rather from the axis are brought to a focus nearer the lens (from [5]).

IV. Coma

Coma is also due to nonlinear effect of Snell's law. There are tangential and sagittal spherical aberrations in the tangential and sagittal planes. It is an off-axis effect. Tangential/sagittal coma~$1/(f\#)^{^2}$.
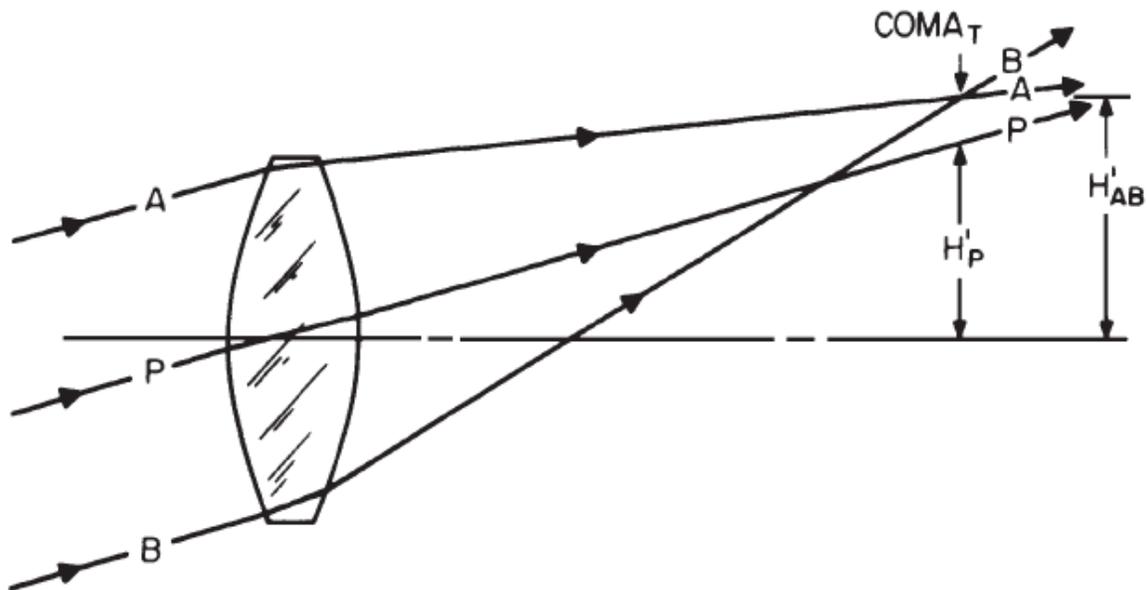

Fig. 6 In the presence of coma, the rays through the outer portions of the lens focus at a different height than the rays through the center of the lens (from [5]).

V. Astigmatism

Astigmatism occurs when the tangential and sagittal (sometimes called radial) images do not coincide. In the presence of astigmatism, the image of a point source is not a point, but takes the form of two separate Lines as shown in Fig. 7. It does not play an important rule in the optics studied in this project.
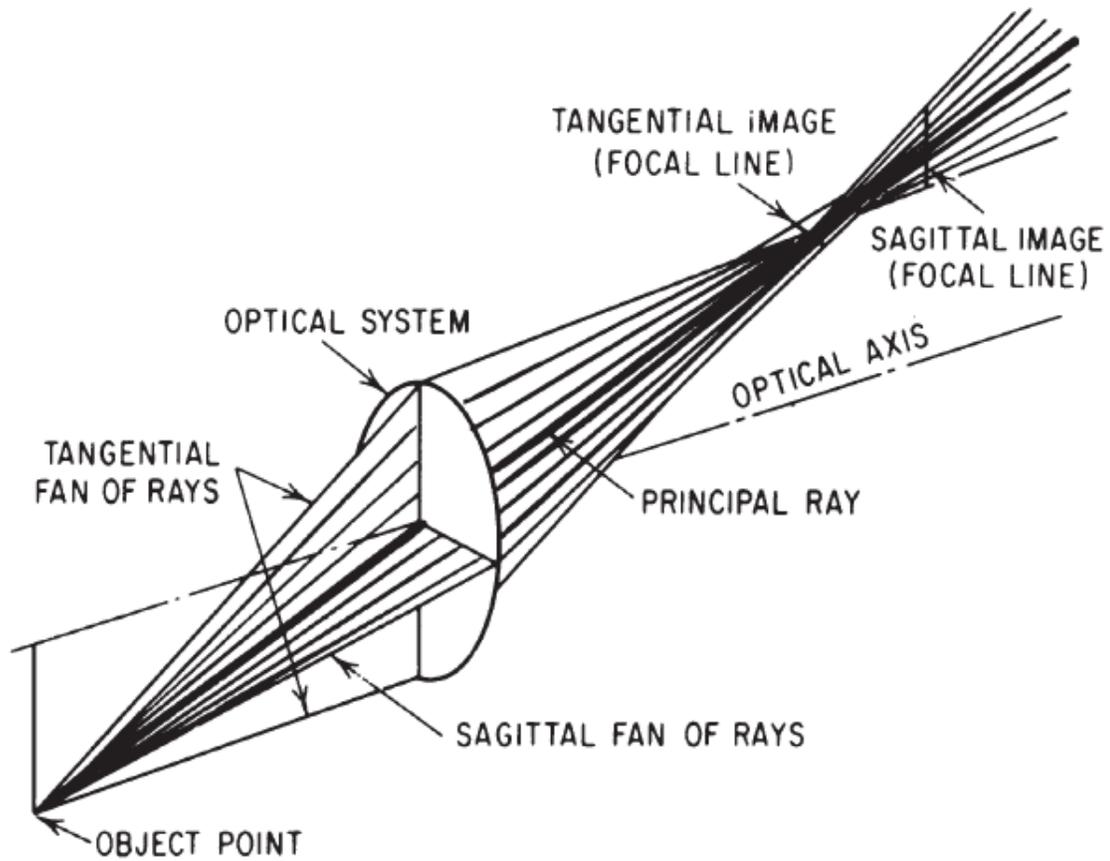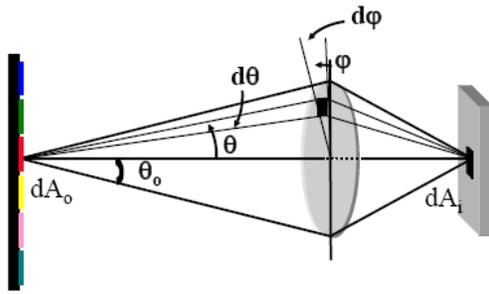
Fig. 7 Astigmatism (from [5])

VI. On/off axis image irradiance

Image irradiance is derived by first integrating over phase space to get the photon flux and then differentiate with respect to image area.

FFf

Flux collected by Imaging Optics

$$d\Phi = \int_0^{2\pi} d\varphi \int_0^{\theta_o} L \cdot dA_o \cos\theta \cdot \sin\theta \cdot d\theta \ \ [W]$$

Image Irradiance

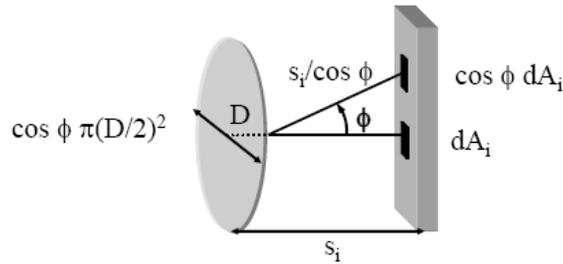$$E = \frac{d\Phi}{dA_i} = \pi \cdot L \cdot (\sin\theta_o)^2 \frac{dA_o}{dA_i} \ \ [W/m^2]$$

$$\Downarrow$$

Sine Condition: $dA_o / dA_i = (\sin\theta_i)^2 / (\sin\theta_o)^2$

$$E = \pi \cdot L \cdot (\sin\theta_i)^2 \ \ [W/m^2]$$

$$\Downarrow$$

$$s_i = f(1-m) \qquad \sin\theta_i = \frac{D/2}{\sqrt{s_i^2 + (D/2)^2}}$$

$$\boxed{E \cong \frac{\pi}{4} \frac{1}{(f/\#)^2 (1-m)^2} L \ \ [W/m^2]}$$

Fig. 8 On-axis image irradiance

$$\cos\phi\,\pi(D/2)^2 \qquad s_i/\cos\phi \qquad \cos\phi\,dA_i$$

On-axis Image Irradiance

$$\boxed{E \cong \frac{\pi}{4} \frac{L}{(f/\#)^2 (1-m)^2} \ \ [W/m^2]}$$

$\Rightarrow$

Off-axis Image Irradiance

$$\boxed{E \cong \frac{\pi}{4} \frac{L}{(f/\#)^2 (1-m)^2} \cos^4\phi \ \ [W/m^2]}$$

Fig. 9 On/off-axis image irradiance (from [6])

Results and discussion

I. Reflective imaging optics design

Paraboloidal mirror:

The following figure shows the paraboloidal mirror designed in this project, we set D=10f, where f is usually 5mm-10mm to make sure the object is virtually at "infinite", because of the small magnification 0.1. The stop is placed in the focus plane to minimize the blurring effects to be discussed below. By setting the f/# to be 0.25, we actually do not need to use a opaque material to block light at the stop. The image is at the focus plane.

focus plane

$M=f/D=0.1, f\#=f/2y=0.25$

$v(m/s)$

Fig. 10 Paraboloidal mirror designed for this project (top fig. from [5], bottom fig. created by myself).

Spherical mirror:

The following figure shows the spherical mirror designed in this project, we set D=10f, where f is usually 5mm-10mm to make sure the object is virtually at "infinite", because of the small magnification 0.1. For spherical mirror, f=R/2. The stop is placed at R to minimize the blurring effects to be discussed below. By setting the f/# to be 0.25, we

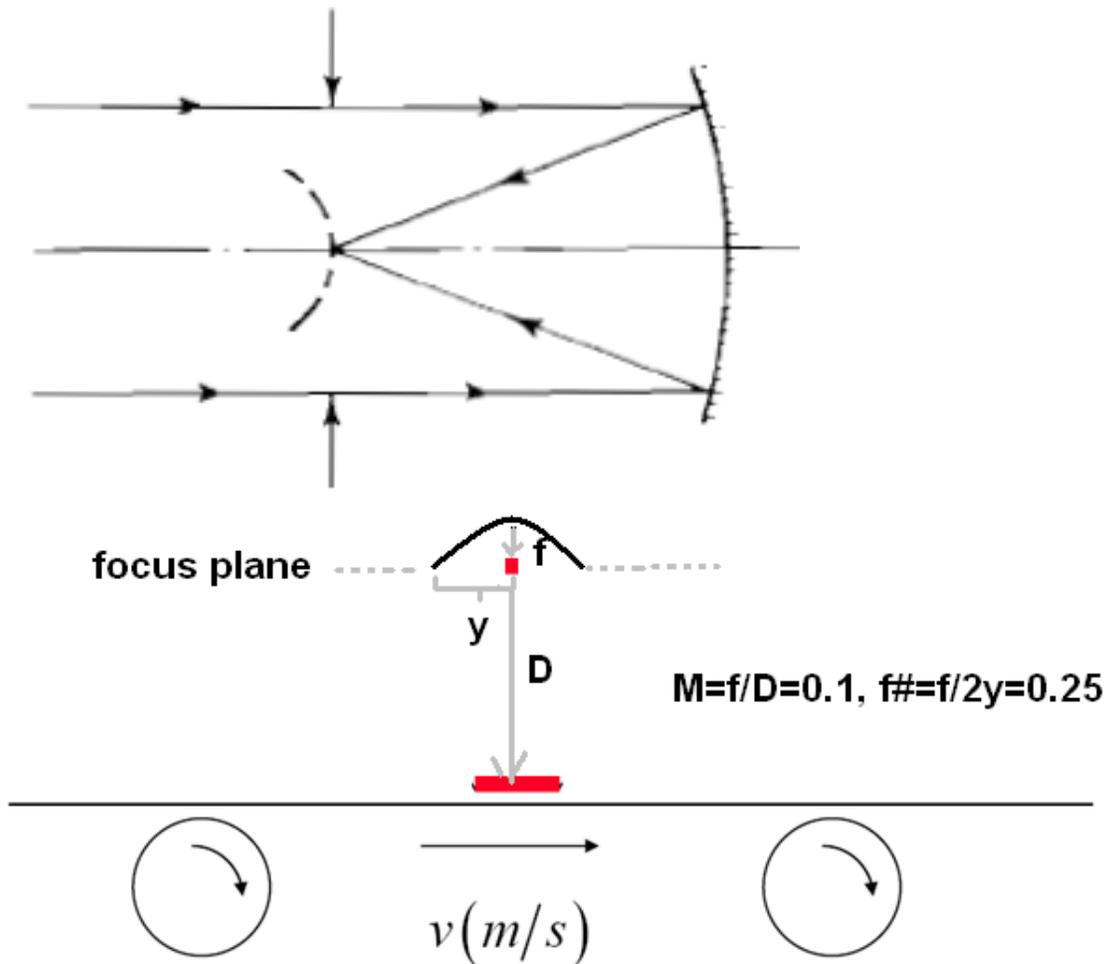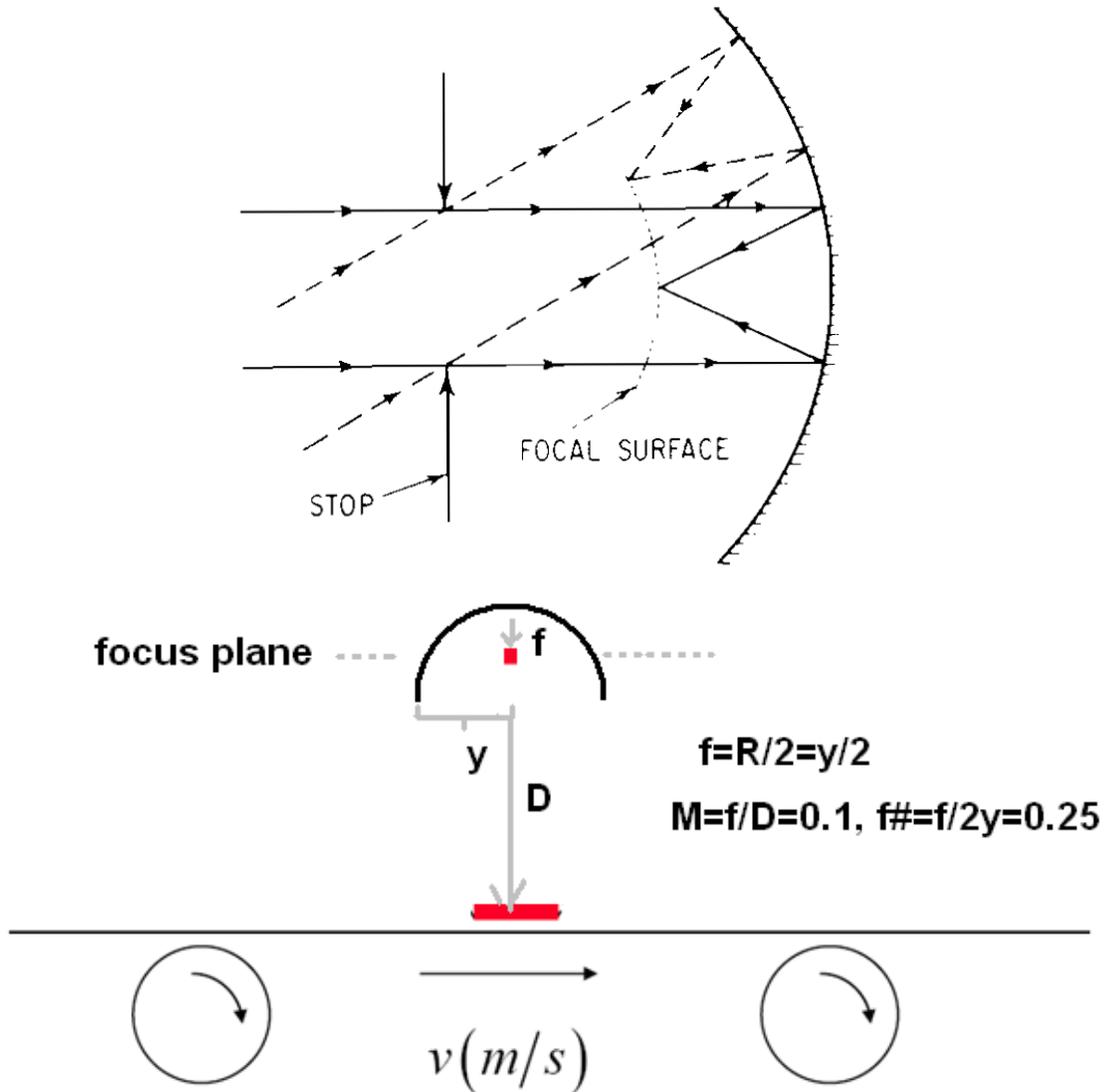actually do not need to use a opaque material to block light at the stop. The image is at the focus plane.

Fig. 11 Spherical mirror designed for this project (top fig. from [5], bottom fig. created by myself).

II. Photon capture capability

The three figures below did a comparison of the three optical systems mentioned above. We get the number of photons captured per L through integrating irradiance over the phase space. We could see clearly that the conventional imaging system is very poor in

this and the near contact imaging system did the best job. However, since the near contact system has serious shortcut such as very hard to illuminate. The reflective imaging systems, although not as good as the near contact system, did a fairly good job. And it does not have the disadvantages accompanied by using the near contact system. So in terms of photon capture capability, the reflective imaging system has the promise for its application.

Conventional imaging: M=0.1 and f/2
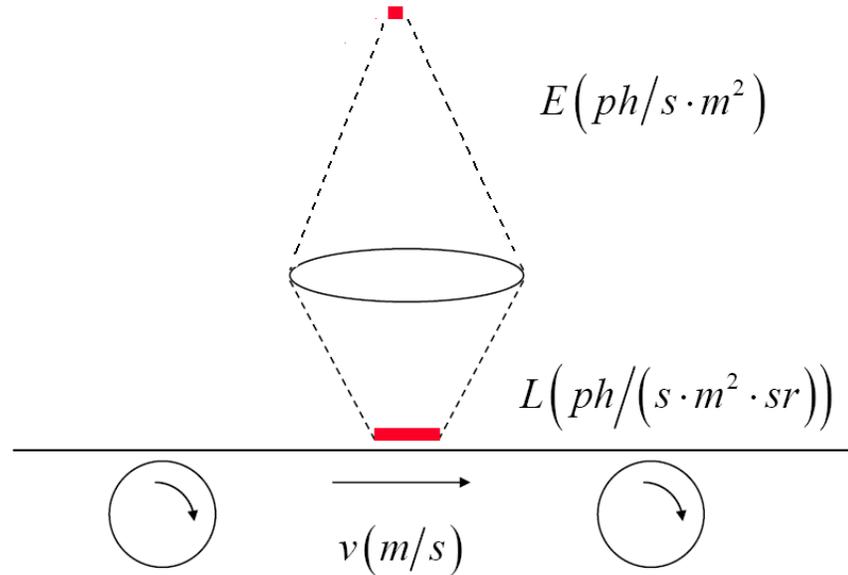
$$\delta_f = 100\,\mu m$$

$$t_d = 21\,\mu s$$
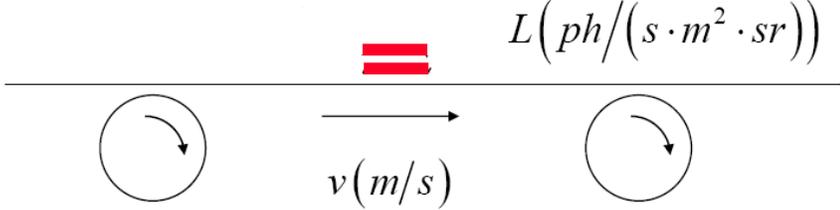
$$d_p = 10\,\mu m$$

$$M_{opt} = 0.1$$

$$f/\# = 2$$

$$T \approx 1, R \approx 1$$

$$E\left(ph/s\cdot m^2\right)$$

$$L\left(ph/\left(s\cdot m^2\cdot sr\right)\right)$$

$$v\left(m/s\right)$$

$$\# photons = E\,t_d\,d_p^2 = \frac{\pi\,T\,R}{1+4\left(1+\left|M_{opt}\right|\right)^2\left(f/\#\right)^2}L\,t_d\,d_p^2 \approx 3.8\times10^{-16}\,L$$

Fig. 12 Photon capture capability for conventional imaging system.

Near-contact imaging: M=1 and f/0.5

$\delta_f = 100\,\mu m$

$t_d = 21\,\mu s$

$d_p = 100\,\mu m$

$M_{opt} = 1$

$f/\# = 0.5$

$T \approx 1, R \approx 1$

$E\left(ph/s \cdot m^2\right)$

$L\left(ph/(s \cdot m^2 \cdot sr)\right)$

$v(m/s)$

$$\# \, photons = E\, t_d\, d_p^2 = \frac{\pi\, T\, R}{1 + 4\left(1 + |M_{opt}|\right)^2 (f/\#)^2}\, L\, t_d\, d_p^2 \approx 3.3 \times 10^{-13}\, L$$

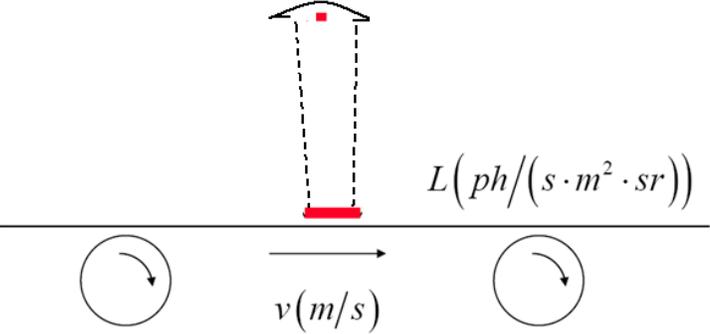Fig. 13 Photon capture capability for near contact imaging system.

Reflective imaging (spherical/paraboloidal mirror): M=0.1 and f/0.25

$\delta_f = 100\,\mu m$

$t_d = 21\,\mu s$

$d_p = 10\,\mu m$

$M_{opt} = 0.1$

$f/\# = 0.25$

$T \approx 1, R \approx 1$

$E\left(ph/s \cdot m^2\right)$

$L\left(ph/(s \cdot m^2 \cdot sr)\right)$

$v(m/s)$

$$\# \, photons = E\, t_d\, d_p^2 = \frac{\pi\, T\, R}{1 + 4\left(1 + |M_{opt}|\right)^2 (f/\#)^2}\, L\, t_d\, d_p^2 \approx 1.3 \times 10^{-14}\, L$$

Fig. 14 Photon capture capability for reflective imaging system.

III. Angular Blurring

The blurring effects are the key issues to prevent the usage of reflective imaging systems, because of their small f/#.

Paraboloidal mirror:

The following figure helps to understand the paraboloidal mirror blurring effects. The parabola is for from an aplanatic (spherical and coma free) system. Since it is not diffraction limited system, we do not need to evaluate the diffraction limited bluring. The spherical aberration is 0 due to all the on-axis light is just reflected to the focus point. The astigmatism is 0, because stop is at the focus plane. For the tangential coma, the focus length of off-axis light is $F=f+x=f+y2/4f$, for an f/0.25 paraboloid the marginal zone focus length is twice that of the paraxial zone and the magnification is correspondingly large. Thus, if the object has a finite size, the image formed by the marginal zones (90 degree field angle) of this mirror will be twice as large as those from the axial zone. This is, of course, nothing but ordinary coma (the "variation of magnification with aperture"). The parabola is aberration-free only exactly on the axis. We can also derive the sagittal coma: $Up/16(f/\#)2\sim Up$. Because the sagittal coma is usually larger than the tangential coma, we use it to evaluate the blurring. The optical view angel is about 1 Radians (object (web) size=20cm, D=10cm), with the typical numbers, thus the blur is proportional to field angle Up. The maximum blur evaluated this way has a intolerable large value: 1 Radians, as large as the object it self. Thus it is not ok to use a single parabola for image with f/0.25.

Solution for paraboloidal mirror:

The solution to use an f/0.25 paraboloidal mirror is to make its view angle only 1/64 of conventional imaging system (f/2). *In other words, the key is to reduce the object size- Use multiple paraboloidal mirrors to image different parts of the web. In this case, the advantage of photon capture with a small f# (for example, 0.25), can be retained. But the fabrication cost increases.*
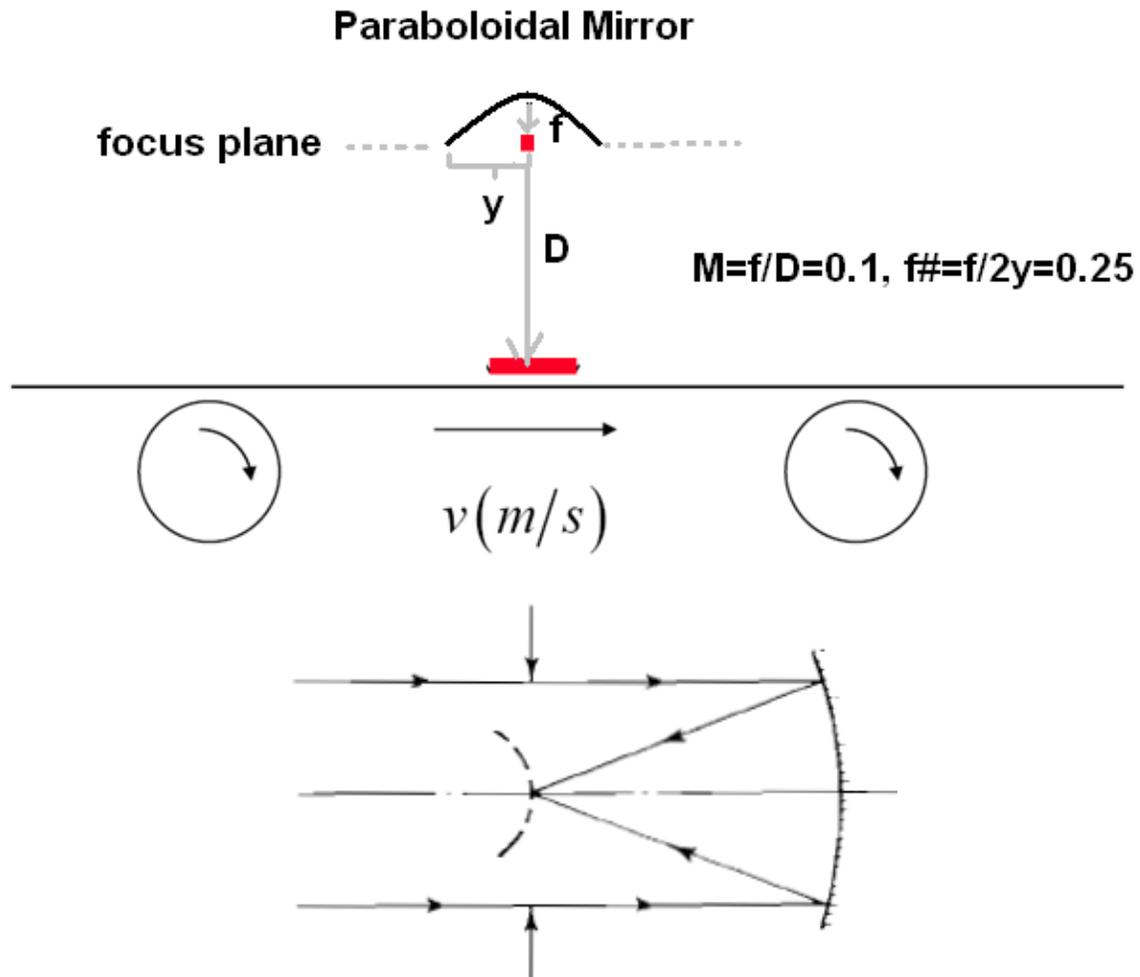
Paraboloidal Mirror

focus plane

y

D

$M=f/D=0.1$, $f\#=f/2y=0.25$

$v(m/s)$

Fig. 15 Paraboloidal mirror configuration (top fig. created by myself, bottom fig. from [5]).

Spherical mirror:

The following figure helps to understand the spherical mirror blurring effects. The parabola is for from an aplanatic (spherical and coma free) system. Since it is not diffraction limited system, we do not need to evaluate the diffraction limited blurring. The spherical aberration is 0.0078/(f/#)3=0.5 radians, 512 times more than conventional imaging system, this just makes this system intolerable. The coma is 0, which is an intrinsic property of spherical symmetry of this mirror. The astigmatism is 0, because stop is at the focus plane. Thus it is not ok to use a spherical mirror for image with f/0.25.

Solution for spherical mirror:

The solution to use a spherical mirror is to make its f number larger. f/0.5 works with reduced blurring=0.0625 radians, but photon# also reduces to 7.7E-15.
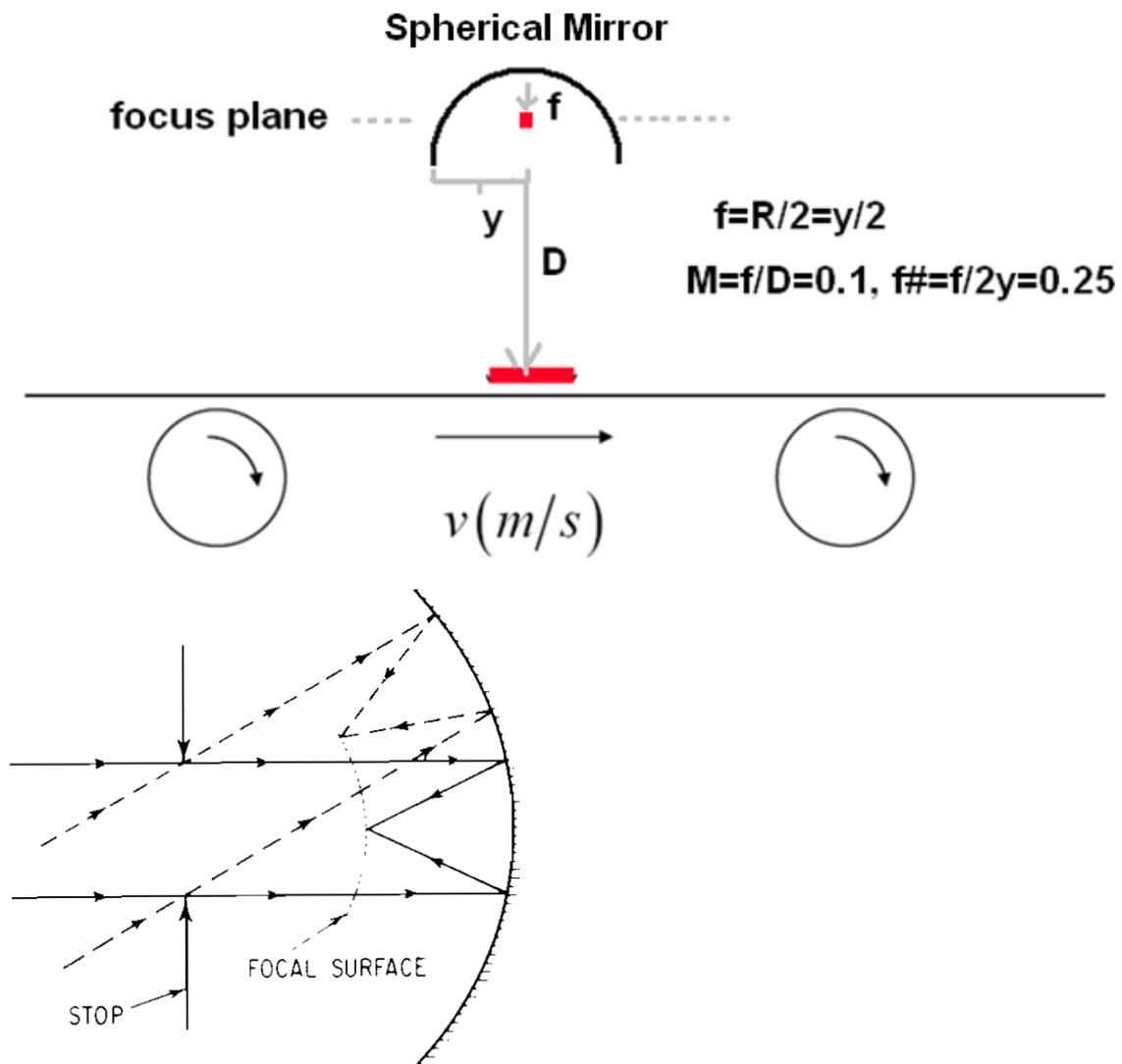

Fig. 16 Spherical mirror configuration (top fig. created by myself, bottom fig. from [5]).

Conclusion

The Conventional Imaging System:

Low photon capture capability.

Near Contact System:

Excellent photon capture capability.

Hard to illuminate the surface.

Requires the same length of sensor as the web width.

Reflective Imaging System:

Fairly good photon capture capability.

But strong blurring effects.

Need a trade-off f/# for reasonable photon capture and blurring effects.

- **Spherical mirror:**

Fairly good photon capture capability.

The blurring is limited by a constant spherical aberration over field angles.

Solution: Use relatively large f/# (for example, 0.5).

- **Paraboloidal mirror:**

Fairly good photon capture capability.

The blurring is limited by coma proportional to field angles.

Free of chromatic aberration.

Solution: The key is to reduce the object size- Use multiple paraboloidal mirrors to image different parts of the web. In this case, the advantage of photon capture with a small f# (for example, 0.25), can be retained. But the fabrication cost increases.

References

[1] http://www.image-acquire.com/canon/canon_pixma_mini320_compact_photo_printer.html

[2] Tom Harris, http://computer.howstuffworks.com/laser-printer.htm/printable

[3] John C. Seymour, Patent Application US 2005/0099795

[4] F. Pease, Stanford EE 317 class notes, April 6 2007

[5] W J. Smith Modern Optical Engineering 3rd edition, McGraw-Hill Press

[6] Peter Catrysse, Imaging and Pixel Optics presentation, Stanford Psych 221, 2002

[7] Peter Catrysse, Printer_Misprint_Optics overview, March 3 2009