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Notes Relating to the Design of

a High Quality Image Sensor

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ABSTRACT

Some of the information that was used in arriving at a design for a high quality image input device is documented. The device uses a PIN photo-diode directly coupled to an FET-input op-amp as the sensor and two moving-iron galvanometer-driven mirrors as the deflection system. The disadvantages of a system like this are its long random access time (about 4 milli-seconds) and the long settling time of the diode-amplifier system (about 1 milli-seconds). In almost all other respects such a sensor is superior to other known image sensors. Pictures taken with this device have shown that some of the difficulties experienced in image analysis can be directly traced to the low quality of images read in through vidicons and image dissectors.

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ADVANTAGES OF A MIRROR-SCANNING SYSTEM USING PIN-DIODES AND OPTICAL SCANNERS:

While systems employing a single photo-diode and a mechanical deflection system are slow in some respects, they do offer many advantages over more commonly used image sensors such as vidicons and image dissectors. Most of these advantages can be traced to the use of a single sensing element and the resulting uniformity in sensitivity and resolution and the better geometric accuracy of the mechanical deflection system compared to one utilizing electron-optics.

A system such as the one described here is cheap, small, stable, reliable, repeatable, has low geometric distortion, high sensitivity, high resolution, low scatter, low noise, low hystereses, large dynamic range, excellent linearity of signal, resolution uniformity over its field of view, good over-load recovery, low blooming, requires only low-voltage power, has wide spectral sensitivity, good quantum efficiency, and is unaffected by external magnetic or electric fields.

Such a system has to be carefully designed, however, since with only a single sensor integrating incoming photons, one has to be very careful about gathering enough light, controlling noise, offsets, and temperature drift. The same problems are faced in the design of an image dissector system of course. With vidicon-like devices this is of little concern, since all picture cells are integrating simultaneously.

One solution to this problem is to employ many sensing cells. Arrays of photo-diodes, both linear or circular and two-dimensional, have been built in various configurations, including most recently the CCD devices. With arrays one does lose some of the advantages mentioned above, such as uniformity of response and large dynamic range. This is not to say that CCD arrays will not be the obvious candidate for almost all image sensing applications of the future, including onboard optical navigation for solar system probes.

OPTICAL SYSTEM: SOME EQUATIONS FIRST
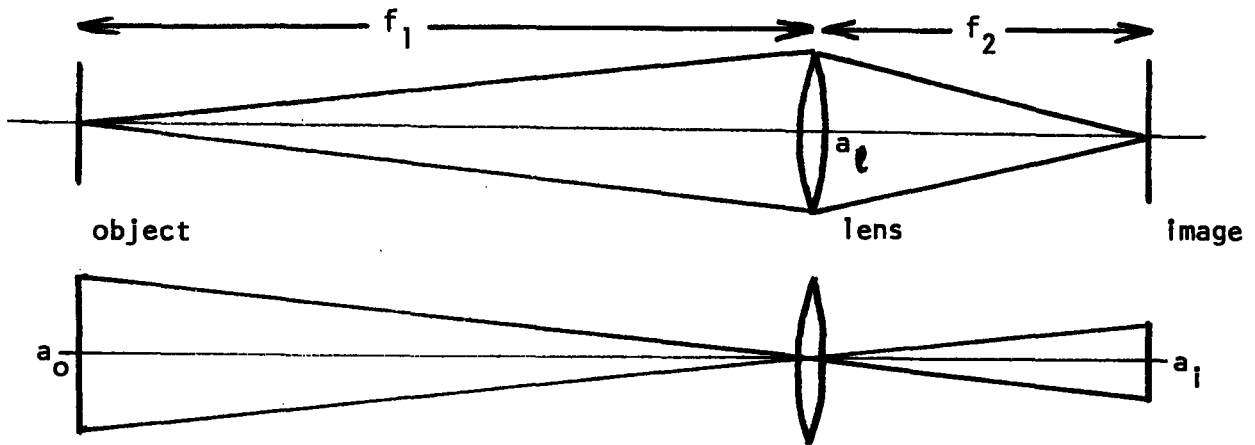
Let the lens have a diameter d and hence an area $a_1 = (\pi/4)d^2$.

Let the aperture have a diameter e and hence an area $a_\ell = (\pi/4)e^2$.

Let the corresponding piece of the object have area $a_o = a_i(f_1/f_2)^2$ *

Then the solid angle per picture cell is $a_i/f_2^2 = a_o/f_1^2$.

Let the irradiance of the object be I_o watt/m^2 and assume that the object is oriented at right angles to the light source and that it has a lambertian surface. Then the object's radiance will be I_o/π watt/steradian-(projected) m^2.

At the lens the illuminance produced by the object area a_o is $(I_o a_o)/(\pi f_1^2)$ watts/m^2. The light flux entering the lens (and subsequently the aperture) is then:

$$\frac{I_o}{\pi} \frac{a_o a_1}{f_1^2}$$

* a_o is the projected area as seen from the lens.

Notice that this does not depend on the focal length of the lens, merely the product of the solid angle per picture cell and area of the entrance pupil. Equivalently is can be thought of as depending on the product of the area on the object corresponding to one picture cell and the solid angle occupied by the lens as seen from the object.

If we remember that $a_o = a_i (f_1/f_2)^2$ and $a_1 = (\pi/4).d^2$ and define the effective f-number N_e as f_2/d, then we get:

$$\frac{I_o}{4} \frac{a_i}{N^2_e}$$

This second equation for the amount of light reaching the detector again does not contain the focal length explicitly, merely the ratio of aperture area to the square of the effective f-number.

OPTICAL SYSTEM: DEFLECTION MIRRORS

LENS

PIN sensor
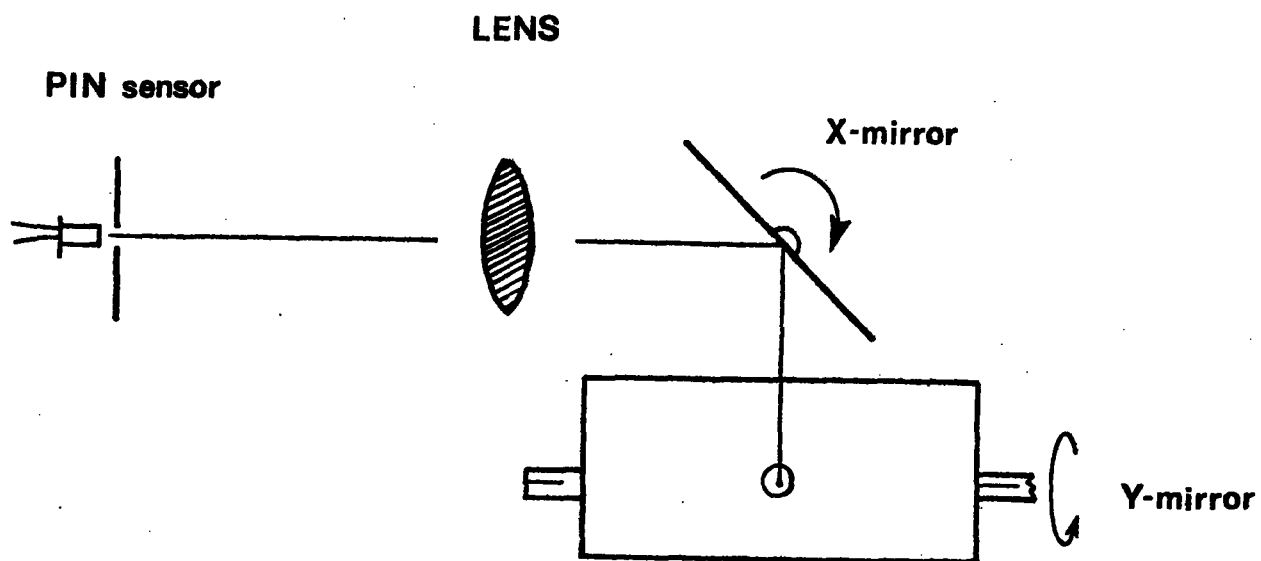
X-mirror

Y-mirror

The photo-diode is mounted behind an aperture on the optical axis in the image place of the lens. The lens is aimed at the square x-mirror, which

is inclined 45° in its resting position to the optical axis. This mirror in turn faces the rectangular y-mirror inclined 45° with respect to the ray connecting it to the object.

Each mirror can be deflected from its resting position by ± θ/2. Let the size of the x-mirror and the dimension of the smaller side of the y-mirror be D. In the worst case (at maximum deflection), the optical path is restricted to a square of size $D\cos(\pi/4 + \theta/2)$. To avoid vignetting then, the entrance pupil of the lens should be no larger than this.

> Example: x-mirror 1" x 1", y-mirror 2" x 1", maximum deflection ± 12°. The entrance pupil should be no larger than $25.4 \times \cos(57°) \approx 14$ mm. For a lens of 75mm focal length this would imply operation at lens openings less than $75/14m \approx 5.6$. The area of the entrance pupil is $a_1 \approx 150°$ mm .

Evidently, the area of the entrance pupil directly determines the amount of light that can be gathered and hence ought to be as large as possible. The larger it is the shorter the time needed to integrate sufficient current from the photo-diode for a given signal/noise ratio. (Alternately, the wider the allowable band-width of the analog circuit amplifying the diode current). Unfortunately, the inertia of the mirrors increases as the fourth power of their size and the random access settling time varies inversely as the cube root of inertia. There is a clear trade-off here between integration time, which varies inversely as mirror size squared and settling time which varies directly as mirror size to the 4/3 power.

Secondary effects of large mirror and lens size include reduction in the depth of field, higher sensitivity to imaging defects such as spherical aberration and minor image degradation due to mirror flexure. Our 1" mirrors represent a compromise between settling time ($\approx$ 4ms) and integration time ($\approx$ 1ms).

By the way, note that the deflection of the optical path is twice the mechanical rotation of the mirror. So for a mechanical peak-to-peak deflection of θ, the optical path will be deflected 2θ peak-to-peak. It is quite possible that one does not wish to utilize the full deflection available. This has to be paid for in terms of smaller picture cells and hence less light available to the sensor.

OPTICAL SYSTEM: APERTURE

The total deflection in each axis is 2θ. If we aim for an image tessela-
tion into n x n picture cells, each will have an angular extend of $2\theta/n$.
From this we can calculate the solid angle per picture cell. Notice that
the aperture as seen from the center of the lens occupies the same solid
angle. Clearly then the amount of light captured by the aperture is inde-
pendent of the focal length -- a larger focal length simply results in a
larger, dimmer image and the correspondingly larger aperture ends up in-
tercepting the same amount of light. The lens can be chosen with any
convenient focal length available.

Circular apertures are easy to make in small sizes and do not require
special alignment with the mirror axes. Further it is convenient with
circular apertures to allow a small amount of overlap between adjacent
picture cell areas. Typically the angular diameter of each picture cell
will then be $2\sqrt{2}\,\theta/n$. So each picture cell corresponds to a solid angle
of $(\pi/4)(2\sqrt{2}\,\theta/n)^2 = 2\pi(\theta/n)^2$.

> Example: $\theta = 25°$ (.44 radian), n = 1024. Angular di-
> ameter of picture cell is $\approx$ 4 arc minutes (1.2 milli-
> radian). Each picture cell has a solid angle of 1.1 x
> 10^{-6} steradians. If we pick a lens of 75 mm focal
> length, the diameter of the aperture should be 90μm.

Evidently, the solid angle per picture cell directly affects the amount of
light received by the photo-diode. We cannot increase the total deflection
of the mirrors much, without increasing vignetting or reducing the size
of the entrance pupil. Only the resolution presents a possibility for
trade-off. The amount of light collected will be inversely proportional
to the total number of picture cells into which the image is divided.
We chose 1024 x 1024 as a compromise between the need to gather enough light
and the need for a reasonable amount of resolution.

OPTICAL SYSTEM: DIFFRACTION

Aside from the problem of getting enough light per picture cell, there are
other limitations on the maximum resolution achievable. Random jitter
and drift in the mirror driver system limits one to about 4096 x 4096
resolution. Diffraction is another effect of importance. The angular
diameter of the central blob of the diffraction pattern for a lens of
diameter d is $2.44\lambda/d$, where λ is the wavelength of the light used.

> Example: For an entrance pupil of 14mm and a wavelength
> of 700nm one gets .42 arc minutes (.12 milli-radian).
> This will limit a system with mirrors of the size speci-
> fied to a maximum resolution not much more than 4096 x
> 4096. We picked 700nm for the wavelength here since it
> represents the area of the spectrum where the product
> of the incandescent lamp power output times PIN photo-
> diode sensitivity is maximal.

To summarize: the light flux received by the photo-diode is proportional
to the product of the area of the entrance pupil and the solid angle per
picture cell. The former is limited by the size of the deflection mirrors
and the latter by the number of picture cells that the image is divided
up into.

IRRADIANCE AND DIODE SENSITIVITY:

The irradiance of sunlight is about 1 kw/m^2; (the illuminance is about
100,000 lux). Of the radiant energy about 570 w/m^2 falls in the visible,
near ultra-violet and near infrared to which PIN photo-diodes are sensi-
tive. In this band of energies the quantum efficiency of these detectors
is around .65 electrons/photon and this gives rise to an average respons-
ivity of about .35 amps/watt. The current produced by such a diode when
exposed to full sunlight is then around 200 amps/m^2 of surface area.

> Example: For the UDT PIN-020A, with a sensitive area of
> .5 mm in diameter and hence an area of 2 x 10^{-7} m^2, this
> comes to 40µA.

Very well lit interiors give rise to about one hundredth of that (in fact
the recommended illuminance of work surfaces for precision work is 1000
lux). We expect then a detector response of 2 amp/m^2. A 200W incandescent has
a luminous efficiency of about 20 lumen/watt and so produces 4000 lumen --
at one meter this gives rise to 318 lux. Because the incandescent lamp
produces a lot of deep red and near infra-red the response to the diode
will be better than indicated by that figure. In fact, a 200 watt incan-
descent bulb produces a photo-diode response of around 2 amp/m^2 at a dis-
tance of one meter.

Let us use this in further calculations keeping in mind that this figure
varies widely. On my office desk, well lit by fluorescent lamps, it is
only a quarter of the indicated figure, while a single 650 watt quartz-
iodide sun-gun with reflector produces a response an order of magnitude
larger at two meters.

ELECTRICAL SYSTEM: DIODE CURRENT TO BE EXPECTED

The above current density has to be modified now to reflect the presence
of the image forming system and the aperture defining the picture cell,
since we obviously do not simply expose the diode to the incident flux.
That is, the diode-current we can expect is:

$$\frac{I_o}{\pi} \frac{a_o a_1}{f_1^2}$$

Where I_o is 2 amp/m^2, a_1 is the area of the entrance pupil and a_o/f_1^2
is the solid angle per picture cell.

Example: I_o = 2 amp/m^2, a_1 = 1.5 x 10^{-4}m , a_o/f_1^2 =
1.1 x 10^{-6} steradian; photo-diode current = 1 x 10^{-10}
amp, that is, 100 pA. This then is the current generated
by the diode placed behind a 90 μm aperture in an f5.6
optical system with a focal length of 75mm, when it is
looking directly at a lambertian surface, which is in
turn directly illuminated in a very bright interior
location. For surfaces not oriented in the optimal
way, and those that are not perfectly white, the output
will be lower (for specular reflections in turn it will
be much larger).

ELECTRICAL SYSTEMS: AMPLIFICATION NEEDED

In order to make this signal useful to a computer it will need to be con-
verted to a voltage and amplified considerably. The best way of performing
the first step of this process is to connect the diode directly to the
differential inputs of a FET-input op-amp with a large resistor in the
feedback path. The diode current ends up flowing directly into this
resistor and the voltage at the output can be determined by Ohm's law.
Clearly it will be advantageous to use as large a resistor as possible.
There is an upper limit due to the effects of leakage currents and re-
duction in band-width of the amplifier.

> Example: Our 100 pA passed through a 50MΩ resistor
> produces 5mV.

How much further amplification is needed? Typical A/D convertors have in-
puts from -10V to +10V and produce 12 bits at their output. That is, one
quantum corresponds to 5mV. If we let our full-scale value of 100 pA
correspond to 100 of these units (or .5 Volt) we need a gain of 100.
One quantum on the A/D corresponds to 1 pA photo-diode current (and this
in turn amounts to a scene irradiance of about 50 mW/m).

This arrangement allows a fairly large dynamic range at the high end to
deal with specular reflections (which can easily exceed other values by
an order of magnitude) and yet allows us to measure intensities to about
1% accuracy. There is no sense in aiming for anything more accurate since
light-source intensity fluctuations, surface irregularities, movement of
reflecting bodies in the room nd so on give rise to fluctuations of a
percent or so anyway. Also, as we shall see, it is hard to measure currents
smaller than a pico-amp in a time as short as a milli-second. Note that
a pico-amp flowing for one milli-second corresponds to a charge of one
fempto-coloumb or about 6000 electrons!

CURRENT AND VOLTAGE: NOISE

A major limitation on the minimum illumination that will produce acceptable output signals is the noise generated by the diode, the op-amp and the feed-back resistor. All of these quantitites vary with the square-root of bandwidth. It is best to refer back all noise amplitudes to an equivalent current through the diode.

The diode itself produces a noise-current: $i_d \sqrt{\Delta f}$

The op-amp produces a noise-current: $i_n \sqrt{\Delta f}$

The op-amp also produces a noise-voltage, v_n: $v_n / R \sqrt{\Delta f}$

Finally, the feedback resistor contributes a noise current: $\sqrt{4KT/R \Delta f}$

Here Δf is the band-width of the amplifier, T is the temperature of the resistor in degrees Kelvin, k is Boltzmann's constant. At room temperature, $\sqrt{4KT} \approx 1.29 \times 10^{-10}$.

> Example: A PIN-020A diode produces 3×10^{-15} amp/Hz$^{1/2}$.
> A 50 MΩ resistor at room temperature contributes 18×10^{-15} amp/Hz$^{1/2}$. A Burr-Brown 3521L FET-input op-amp produces about 1.4×10^{-15} amp/Hz$^{1/2}$ current noise and the equivalent of $.6 \times 10^{-15}$ amp/Hz$^{1/2}$ in 50MΩ due to voltage noise. It is clear that in this case the feedback resistor is the dominant noise-source. At 1 kHz band-width we should expect a total of about .7 pA rms noise.

OFFSET VOLTAGES IN THE OP-AMP:

Unfortunately, noise is not the only limiting factor. There are offset currents and voltages in the op-amp and these vary with external parameters such as temperature, supply voltage and time. Let us consider voltages first. There is an initial offset which is of little consequence in it-self since it is constant and can be cancelled out by additon of a suitable potentiometer adjustment. Unfortunately, this introduces a temperature sensitivity which increases in direct proportion to the amount of offset one has to compensate. This is in addition to the inherent temperature sensitivity of the offset. Offset voltages also vary with supply voltage, so good regulation of supply voltage is important. Finally there is a small aging effect and so the offset voltage drifts with time.

Example: Burr-Brown 3521L again, initial offset 250µV.
This is large (corresponding to a 5pA current in the
50MΩ resistor), but can be cancelled by a suitable cir-
cuit. The simple potentiometer offset adjust introduces
an extra .5µV/°C drift per mV of offset corrected. A more
sophisticated circuit produces only .14µV/°C extra drift
per mV of offset cancelled. The temperature coefficient
of the amplifier itself comes to ± 1µV/°C, which swamps
the above. (This corresponds to a .2pA current in the
50MΩ resistor for a 10° change in temperature). The off-
set also changes by 25µV per Volt of power-supply fluctuation
and by 10µV per month.

It is clear that choosing the feed-back resistor large enough one can make the effect of these offsets and offset-drift appear small in terms of the equivalent input current.

BIAS CURRENTS IN THE OP-AMP:

There is a bias current flowing in the input leads which can be simply cancelled by connecting the second input through a resistance equal to the feed-back resistance to ground. This bias current also doubles every 10°C but can be ignored provided the above precaution is taken. The currents flowing into the two input terminals do not match exactly, however, and there is a (smaller) input difference current. This current also doubles for each 10°C increase in temperature. Finally there is a drift in the input current with supply voltage.

> Example: Burr-Brown 3521L again. The initial bias
> current is -10 pA. This can be ignored if the inputs
> are connected through the same resistance as indicated.
> There is however a ± 2 pA difference in the current
> flowing into the two leads at 25°C. This of course can
> be compensated for by the offset adjustment, but this
> current doubles with every 10°C temeprature increase.
> So at 35°C it will have drifted up to 2pA. This clearly
> is the main limitation on the smallest diode current we
> could hope to measure with this particular amplifier. The
> input bias current also changes by 1 pA/volt change in
> supply voltage -- for a reasonably well regulated supply
> this can be ignored.

A system using this op-amp is limited by the temperature drift of the differential bias current to measurements down to about 2 pA.

CHOICE OF DIODES AND OP-AMPS:

Since the mirror deflection system is the main cost-component of an
image-sensing system of this kind ($\approx$ $2K), one can afford to think in
terms of high-quality photo-diodes and op-amps. The PIN-020A photo-diode
is about as high quality as is presently available ($\approx$ $50), the Burr-
Brown 3521L FET-input op-amp is also pretty good ($\approx$ $50). Some improve-
ment is possible, however, and the Optical Electronics OEI 9733 (at
$100) has the following performance figures: current-noise = 1 x 10^{-15}
amp/Hz$^{1/2}$, voltage-noise = 35 x 10^{-9} volt/Hz$^{1/2}$, initial offset voltage =
100μV, offset voltage drift = ± 1μV/°C initial bias current = 100 x 10^{-15}
amp, differential current 10 x 10^{-15} amp!

With a 100 MΩ feed-back resistor and 1 kHz band-width, the following
figures obtain:

> PIN-020A produces 3 x 10^{-15} amp/Hz$^{1/2}$ noise current, the
> OEI 9733 amplifier contributes another 1 x 10^{-15} amp/Hz$^{1/2}$
> in current noise, the equivalent effect of the voltage
> noise comes to .35 x 10^{-15} amp/Hz$^{1/2}$. The resistor it-
> self produces 13 x 10^{-15} amp/Hz$^{1/2}$, the dominant factor.
> At 1 kHz bandwidth one can expect about .5 pA noise current.

> The 1 μV/°C offset voltage drift amounts to .1 pA in the
> 100 MΩ feed-back resistor for a 10°C temperature change.

> Also, a 10°C change in temperature will produce only a
> .01 change in differential bias current.

It is clear that now the noise is the limiting factor, mostly contributed
by the feedback resistor. This system allows measurement down to about
.5 pA.

SYSTEM COMPONENTS:

The system uses two G-300PD Optical Scanners from GENERAL SCANNING INC. mounted in an XY-300 frame and driven by CCX-100 controllers (which include PD-203 position and velocity circuit, CC-103 Control Circuit, A-103 Driver Amplifier). The computer controls these two devices through ± 10 volt, 12 bit D/A's -- it also has access to the position read-back via a ± 10 volt, 12 bit A/D.

The optical system uses a cheap, standard 75 mm focal length lens with C-mount used in vidicon and 16 mm motion picture cameras. The PIN-020 diode made by UNITED DETECTOR TECHNOLOGY is mounted behind a circular aperture obtained from EDMUND SCIENTIFIC. The amplifier is housed integrally with the diode and utlizes a Burr-Brown 3521L FET-input op-amp for the current to voltage transducer, and a Burr-Brown 3522L FET-input op-amp for the further amplification by a factor of 100. The output is read by a ± 10 volt, 12 bit A/D.

ACKNOWLEDGEMENTS

47 pf

1.02M

	GAIN	NOISE	FEED BACK
HIGH		≈ 1 mV P-P	9.94 K
ULTRA HIGH		≈ 25 mV P-P	11.024 M
VERY HIGH		≈ 5 mV P-P	113.2 K

47 M

8
2
3521L
6
3
5
1

PIN 020A DIODE

47 M

10K

161 pf

2
8
3522L
6
3
+15

50 Ω

10K

2.7K

2
1741
6
3
+

Over-Exposure Warning LED

10K

-15V

2N3906

820K

3.3M

5.6K

10V

+15

+15

PIN
E
H
D
S

20 Ω

+15

1 uf

PIN 7

10 Ω

-15V

1 uf

PIN 4

OUT