Using PSD's For Auto Focus Systems

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***Abstract* - Optical PSD's (Position Sensitive Detectors) as applied to autofocus systems are considered in this paper. Both conceptual and analytical backgrounds are presented. The effects of PSD processing on the performance of a PID servo loop (Proportional-Integral-Derivative) are also discussed. Presented are a series of formulae and guidelines for implementing a PID control loop using a PSD module.**

I. Introduction

PSD's have been available for many years. In recent years the available analog and digital components and tools have improved to allow better integration of PSD modules. This has allowed for better optimization of the resulting position data such that detector limited systems can be more easily realized. In turn, this allows system designers to develop more aggressive applications where PSD's are used. While this paper addresses auto focus systems specifically, other PSD applications include beam steering, optic stabilization, 3D position sensing and 3D scanning cameras.

This paper will discuss the structure of the basic detectors, how their outputs must be processed and the circuit design challenges that must be addressed to obtain detector limited performance. Then the application of autofocus systems will be discussed and how the PSD interplays with a typical PID control loop will be examined.

System designers who wish to apply PSD's should always be aware of how they work, where their strengths and weaknesses are. This knowledge is key to obtaining aggressive system level performance and an understanding of how to specify and evaluate PSD module requirements.

Elite provides a family of PSD modules that support high performance autofocus applications. These modules are used as the basis for the optical feedback modeling given in this paper showing the value of their high sample rate and high accuracy.

II. PSD Basics

To the first approximation, a PSD is a large area silicon photodiode with multiple connections on either its anode or cathode. In a one dimensional PSD the optical energy that impinges on the detector surface results in a current that will divide in some proportion between the two anodes. In a properly designed PSD, the ratio of the two currents is directly proportional to the centroid of the optical power density function (i.e. spot shape).

Figure 1 shows the simple case where a laser is focused onto the center of the PSD. As the spot moves towards anode 1, the current at that anode will increase while the opposite anode's current will decrease.

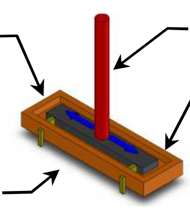


Figure 1

As with any PIN photodiode, the usual parasitic elements must be considered when designing the associated preamplifiers. As a large area photodiode, there will be significant capacitance that will limit the combined detector and amplifier bandwidth.

There will also be a limit on the minimum possible response and rise time based on carrier transit times due to the large mean path distances involved.

What is not common between ordinary photodiodes and PSD's is the ohmic connection between the multiple anode connections. This can be modeled to first order as a simple resistance between anodes. Improper biasing can create current flow between the anodes that will mix with any induced photocurrent. Careful balancing of gains and biasing circuitry can reduce the impact of this inter-electrode resistance.

Once the PSD currents are obtained, the calculation of position is straightforward. Since current is proportional to current, the simplest equation that can be used to compute position would be:

$$X = K(I_1 - I_2) \qquad \text{[Eq 1]}$$

The coefficient K contains the scale factors used to convert the difference in current into distance and the gains of the preamps. The obvious difficulty is that K contains a number of highly variable effects. First, as the total optical power varies, the value of K will have to vary. This effect could easily occur dynamically in any application. Second, the preamp gains would need to be known to better than 1% which will place a significantly higher level of design constraints on that circuitry.

The solution most commonly applied is to normalize the computation in a way that compensates for general signal magnitudes and gains.

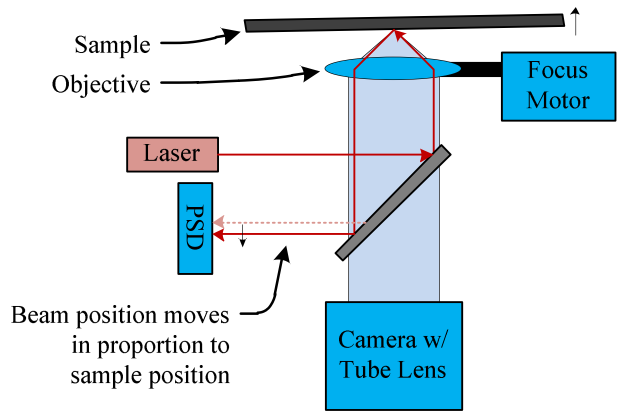
$$X = K_D \frac{(I_1 - I_2)}{I_1 + I_2} \qquad \text{[Eq 2]}$$

Equation 2 is the traditional "difference/sum" normalizing form for ratiometric measurements. The remaining coefficient, K_D, now becomes a constant that represents ½ the physical length of the detector. This form will now automatically compensate for variations in applied optical power (the sum term). This also takes out variations in the average gain of the preamps but does not correct for gain differences.

The units for the result, X, will match those selected for K_D.

III. AutoFocus Using A PSD

Many automated microscope systems require some sort of automatic focus control systems. Performing focusing using direct camera images can be time consuming in systems that perform scanning and capturing of multiple images. One technique that speeds up the process and allows for real time focus control is to combine the camera with a PSD. Figure 2 shows a simple diagram of such an application.



Example Focus Application
Figure 2

In this application, a collimated laser beam is combined with the optical path using an optic that has a very low reflection coefficient in the PSD pick off path. This minimizes the impact on the image energy that is transmitted back to the camera.

The PSD can be operated at any wavelength from the violet to near IR range. Picking a wavelength compatible with the required camera operation necessitate an optical filter to prevent the laser energy from interfering with the camera imaging.

A focus motor controls the position of the objective.

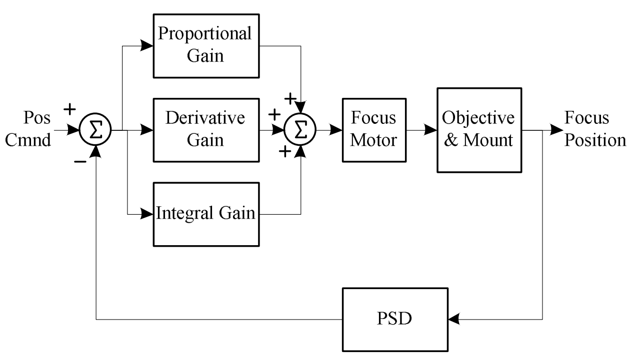
The camera can be used to initially locate the point of best focus. The PSD can be read to obtain the spot position on the PSD that corresponds to best focus. Once that action is completed, the PSD output is used to control the position of the objective.

With the PSD controlling focus, as sample can be translated laterally in the X and/or Y directions the PSD will constantly adjust focus. The sample tilt shown in will be compensated out now as any XY movement occurs. A properly designed PSD can provide more than 100 Hz bandwidth. This will make the focus motor the slowest element in most focus systems and put the loop performance limit there.

III. AutoFocus PID Configuration

PID loops represent a simple and quick way to construct a servo loop. They allow for tuning loop performance without requiring a detailed analysis of servo stability and they relieve the designer of having to understand gain and phase Bode plots. Nonetheless, it is still important to understand the component pieces and their contribution to stability and over all performance.

Figure **3** shows an example focus PID loop. The "Pos Cmnd" will be the desired PSD position that was found to be best focus. The output of the three gain blocks will be the command to the focus motor. For mathematical convenience the focus motor and objective shall be considered as a single block which moves the objective to a position determined by the gain of the motor and the focus motor command input level (this is equivalent to the manner in which a flexure based piezo motor operates).



Example Focus PID Loop

Figure 3

Taking a traditional approach to stability analysis, we will derive the OLTF (Open Loop Transfer Function) first. This allows a more straightforward and simplistic evaluation of the Roth-Hurwitz stability criteria. Classical servo theory operates using LaPlace transforms as a basic context and generically labels for the forward gain path as G(*s*) and the feedback path as H(*s*), *s* being the LaPlace operator. To simplify the math a bit, we will make the following assumptions:

- The computation and update time for the PID calculations and the bandwidth of the PSD transfer function is at least 10 times faster than the slowest element in the loop. This will allow us to set H(s) = 1.
- The combined focus motor and objective will have an impulse response that can be modeled as a simple pole (low pass filter) with gain.

Using these assumptions, the OLTF would be:

$$GH(s) = \left[K_P + K_D s + \frac{K_I}{s}\right]\left[\frac{K_{MO}}{s\tau_{MO}+1}\right] \qquad \text{[Eq 3]}$$

Where:

K_P = PID proportional gain
K_D = PID derivative gain
K_I = PID Integral gain
K_{MO} = Focus DC motor gain
τ_{MO} = Focus motor impulse response time constant (seconds)
The PSD gain is assumed to be 1 (i.e. it reports the input spot position in the same units as input from focus position)

This simple analysis does not include the effects of non-linearity in the focus motor nor the optics. Nor does it include the system disturbances that are common in most implementations (i.e. vibration and other disturbances from outside the focus loop itself). These items can dramatically change the transfer function. In order to keep this exercise useful to some degree, the following will be considered as we choose the appropriate PID settings:

- We will assume that there is a distinct possibility that there may be external high frequency system vibration may enter the system directly into the motor mount, the PSD mount or the sample itself.
- We will recognize that while we are modeling the focus motor with a single pole impulse response, in actuality there are other poles present at higher frequencies that the single modeled pole.

- A primary goal is to have no over shoot as over travel could lead to crashing the objective into the sample.
- Another primary design goal is to achieve an unconditionally stable control loop with reasonable response speed. Moreover, the loop must be reasonably tolerant of component variations.

These assumptions lead us to:

- Disabling the PID derivative term
- Minimizing bandwidth to reduce influence of noise and to reduce response to
- Targeting a Type I loop (i.e. an unconditionally stable loop configuration)

This results in the setting $K_D = 0$ which yields an OLTF of:

$$GH(s) = \frac{K_{MO}\left[\frac{K_P}{K_I}s+1\right]}{s[S\tau_{MO}+1]} \qquad \text{[Eq 4]}$$

If the system can be constrained such that:

$$\frac{K_P}{K_I} \approx \tau_{MO} \qquad \text{[Eq 5]}$$

then this will lead to "pole-zero" cancellation. The effect is to force an unconditionally stable loop with bandwidth limiting established primarily by the focus motor limitations. The OLTF response becomes:

$$GH(s) = \frac{K_{MO}}{s} \qquad \text{[Eq 6]}$$

The closed loop transfer function, which is the impulse response, becomes:

$$GH(s) = \frac{1}{\frac{s}{K_{MO}}+1} \qquad \text{[Eq 7]}$$

If the constraints of Eq 5 can be roughly met, the resulting loop with will meet the stated requirements. The pole-zero cancellation constraint is fairly forgiving and can tolerate 20%-50% in device tolerances before creating loop instability.

The result is a loop with no over shoot whose settling time is limited by the focus motor.

It is important to note that in addition to meeting the criteria of Equation 5, specifically the ratio of K_P/K_I, one must be aware that the magnitudes of the individual terms can be used to adjust the OLTF crossover point (i.e. the 0dB point where the loop gain is 1). Recall that the starting assumption was that the loop sample rate (essentially the PSD update rate) is ten times higher than the OLTF crossover point. Once the pole-zero cancellation is achieved, the next step would be to increase the K_P term (while maintaining the K_P/K_I ratio) until loop cross over approaches approximately one-tenth the ample frequency.

Figure 4 thru Figure 6 show the response to a 30um step command for a PID loop containing a 175 Hz bandwidth focus motor. The PSD is assumed to have a >1KHz update rate (equivalent to Elite's PPSD-1D12B). The graphs show the results when the K_P/K_I ratio is exact and when the K_P term is set ±50% of the exact value.

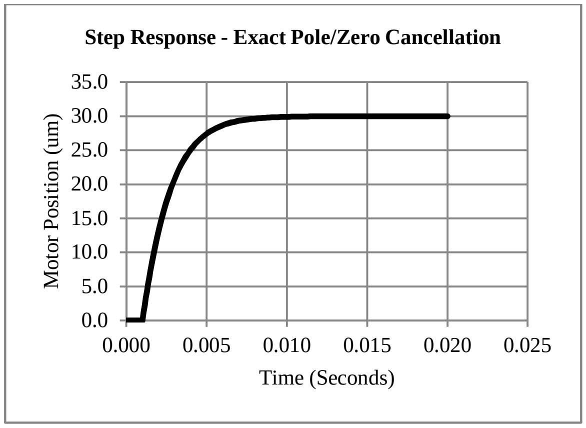


Figure 4

Figure 5 - shows that with the DC gain too low, the response has about 1% over shoot (roughly 0.3um in this case).

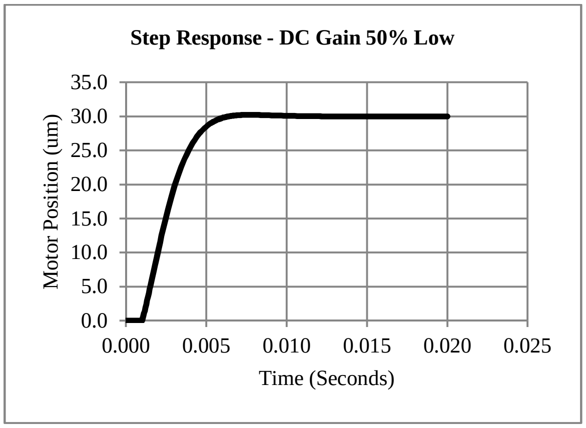


Figure 5

Figure 6 shows when the DC gain is 50% too high. While there is no over shoot, it should be noted that the rise time of this response is faster than the other responses. This can become important if it exceeds the slew rate limit of the motor (the effect of which is not included in this simple model).

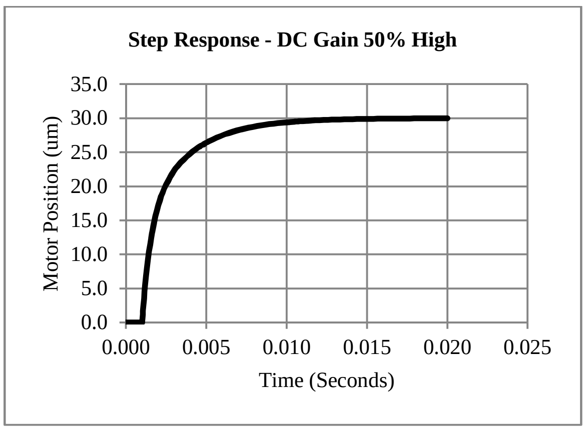


Figure 6

IV. Conclusions

The simple PID model presented has the capability to implement simple pole-zero cancellation to compensate for focus motor low pass filtering effects to create an unconditionally stable loop. This enhances stability of the PID and increases its tolerance to component tolerances and variations between focus motors.

The results show that by properly balancing the proportional and integral gains, a control can be created that allows for >20% variation in motor gain and frequency response without incurring excessive over or undershoot.

The presented data shows the value of using a high sample rate PSD such as Elite's line of PSD Modules which provide both speed and accuracy. Elite's PSD's provide higher sample rates which allow more flexibility in optimizing loop response and protection against loop instability.

For more information on Elite's product line of modules, please visit: elitemodules.com

Or contact us at: contact@elitemodules.com

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