An Introduction to Feedback Control for Optical Systems

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Abstract

The basic concepts and components of feedback control for optical systems are introduced. Open and closed loop feedback configurations are presented and the advantages and disadvantages of each are discussed. A simple and practical use of feedback control to improve optical performance is shown using camera image stabilization as an example. The role of feedback control in optical systems for future applications is discussed.

1 Introduction

Why should optics students learn about methods of feedback control? Control engineering has a long and productive history with large and expensive optical systems. Pointing and tracking control for astronomical telescopes are extremely important to achieving good image quality and, therefore, good science. Advanced military optical systems often involve extensive use of control theory. Applications such as beam stabilization for high energy lasers, vibration reduction for optical systems mounted on aircraft, and tracking for IR and optical sensors all require feedback control to meet their performance requirements. In recent years many other diverse fields have begun to use feedback control in optical systems. Such disparate applications as active aberration control in lithographic lenses, controls for polishing large mirrors, image stabilization of laser guide stars, and even control of quantum systems using lasers, all use feedback control to push the limits of system performance.

But even if the serious optics student chooses to work on smaller, less expensive optical systems, it may still be necessary for them to be familiar with the basic concepts of controls. The availability of inexpensive computing power and the reduction in cost and size of components necessary to implement control systems, have contributed to the proliferation of control systems implemented on smaller, less expensive optical systems.

Finally, the intent of this tutorial is not to teach the details of control theory which can be found in many fine references [6],[7]. Rather it is to expose optical engineers to the basic concepts and components which comprise a typical control system so that they have a fundamental understanding of how feedback control systems work and how they may impact the image forming properties of the system they design.

2 Basic Concepts in Controls

The basic principle of feedback control is to use some measured physical parameter to alter the system dynamics in such a way as to benefit the system performance. So how is this done? And what defines good system performance? The first step is to decide what parameter to control. These could be parameters such as velocity, force, or displacement. Often optical systems use angles or angular rates as parameters to control the system dynamics since they are typically correlated with image motion. This requires some sensing device capable of measuring the parameter of interest. Sensors come in a wide variety of forms depending on what is being measured. Rate gyros and accelerometers are two extremely common sensors used for measuring feedback parameters since they are small, accurate, and relatively inexpensive.

The measured parameter is then used to affect some change in the system response. An example for an optical system might be to measure the angular tilt of a mirror which results in motion of the image. The measured tilt angle is then used to move another optical element to correct for the tilted mirror. The controller, or control algorithm, is a mathematical instruction telling the system how to best move the correcting element. This is not a trivial process and deciding what the best algorithm may be for a particular system is beyond the scope of this paper. Older controller were implemented using analog component and were built up from resistors and capacitors. Modern controllers are typically implemented in software. This makes implementation of complex algorithms much easier and allows for verification that the software algorithm is implemented correctly. The final step is to command the correcting optical element to move. This is done using an actuator. For optical applications this is often a DC motor, piezo, or voice coil actuator. The actuator takes the command from the controller and moves the correcting element. This cycle is continuously repeated real-time as the system changes.

3 Classification of Control Systems

Two general classes of control systems, open loop and closed loop, are typically implemented. These labels are somewhat artificial and, in real systems, the line between the two classes is often blurred.

3.1 Open Loop Control System

A schematic of a typical *open loop* control system is shown in figure 1. An open loop controller is one in which the current measurement value is sent to the controller. The controller in this case consists of a precalibrated algorithm or model of the system. The open loop controller does not have any feedback, or check, to see if the input has achieved the desired goal. The effectiveness of the correction lies in the accuracy of the model and any deviation of the system response from the model will not be corrected.

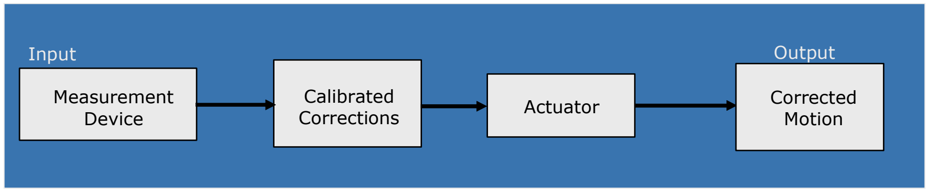

Figure 1: Block diagram of a typical open loop controller. A sensor, controller, and actuation device are used to make a correction to the system.

The open loop controller consists of a sensor to measure the parameter of interest, a controller or precalibrated model of the system dynamics, and an actuation device to provide the movement to the correcting element. Open loop controller are often faster and cheaper to implement that their closed loop counterparts. However, they are not robust to changes in the system. Examples of open loop controllers used for astronomical telescopes include corrections for atmospheric refractive effects as a function of zenith angle and compensation for gravitational sag in the telescope structure.

3.2 Closed Loop Control System

A typical *closed loop* control system is shown in figure 2. The close loop control system is different from the open loop system in that it uses a feedback signal. The command signal is the desired state of the system and the feedback signal is the actual state of the system. The difference of the two form an *error signal*. The controller uses the error signal to determine the best way to move the correcting element. The advantage of this type of system is that it does not rely on the accuracy of a system model. It is therefore more robust to changes in the system or disturbances that are not accounted for.

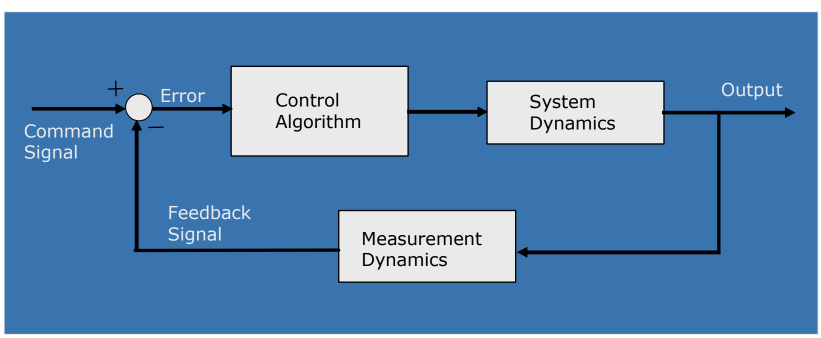

Figure 2: Basic components of a closed loop feedback system. The error signal attempts to force the system to follow the command.

The closed loop control system is more difficult to implement and more costly than open loop control systems. Care must also be taken when determining the control algorithm as an inappropriately designed algorithm can drive the system unstable. A common type of control algorithm is the PID (proportional, integral, derivative) controller. It makes use of the integral and derivative of the error signal to alter the response of the system at various frequencies. The determination of the system gains and controller stability often employs frequency response analysis which is discussed in detail in reference [2]. Some examples of closed loop control for optical systems include pointing and tracking for telescopes, active controls for polishing large mirrors, and adaptive optics systems.

4 Example: Image Stabilization for a Camera

An excellent example of control systems used in optics are image stabilization systems for hand held cameras. Often the limitation for good image quality with hand held cameras is not the optics but the ability of the user to maintain a steady hand while taking the photograph. This results in low frequency jitter or variations of the line of sight during the time of the exposure, resulting in image blur. An image stabilization system can correct much of this blur by sensing the angular rate of change of the camera and moving an optical element in real time to correct the line of sight deviation.

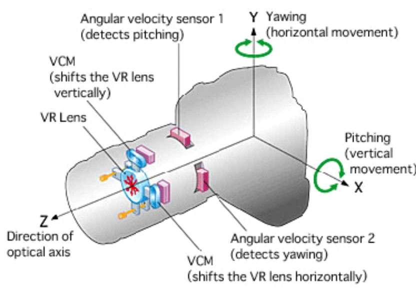

Figure 3: Schematic of the Nikon VR system using angular velocity sensors and voice coil actuators.

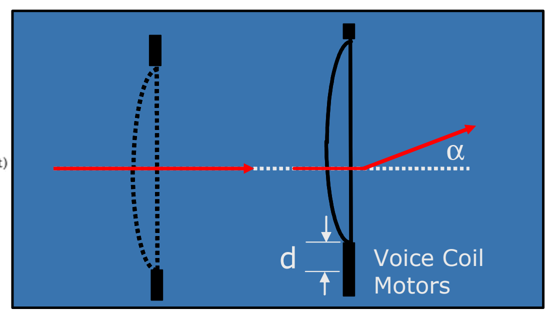

Figure 4: Voice coil actuators decenter the correcting lens to deviate the rays.

Figure 3 shows a schematic diagram of the Nikon vibration reduction system (VR). The Nikon image stabilizing system is implemented within the lens of the camera which allows for tailoring of the control system to the individual properties of that particular lens. Ray deviations can be changed by decentering the controlling lens element as shown in figure 4. The angular shift is given by

$\alpha \cong d/f$ where d is the lens displacement and f is lens focal length.

The lens displacement is achieved by movement of the voice coil actuator. The controlling lens and voice coil actuators can be seen in figure 5 for the Nikon vibration reduction system. The lens tilt has a negligible contribution to the image motion (figure 6)

Figure 5: Nikon VR lens element and voice coil actuators

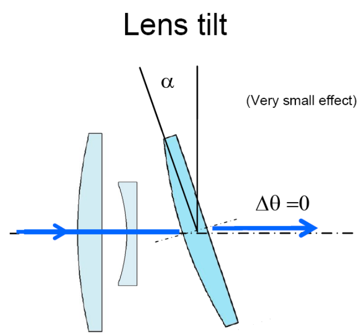

Figure 6: Lens tilt has minimal effect of ray deviation

Figure 7 conceptually illustrates the process of minimizing the image blur. The system uses angular velocity sensors (rate gyros) to measure the amount of line of sight deviation once the shutter has been depressed. The sensor package consists of two orthogonal rate gyros and three voice coil actuators which allow the system to correct for line of sight deviations in both pitch and yaw. The controller uses the angular rate information to command the displacement of a voice coil actuator which then decenters the controlling lens element. As the lens is displaced, the decenter of the lens causes the rays to be bent back toward the original location on the CCD array (or film) when the shutter was first opened.

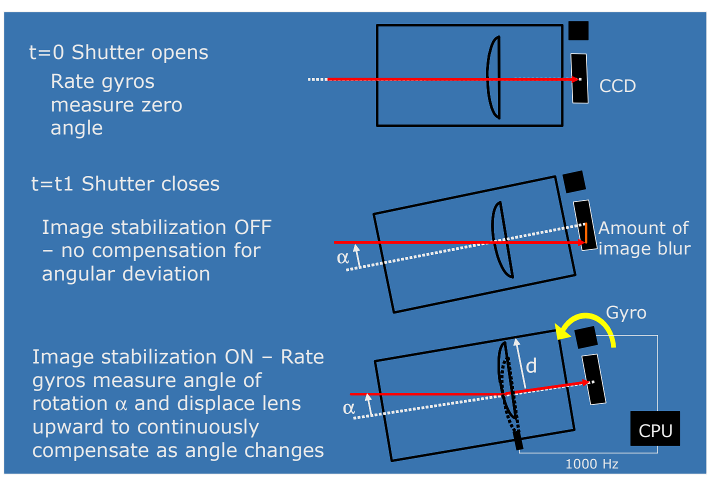

Figure 4: Image stabilization systems actively minimize the amount of image blur

The process of measuring the angular rates and moving the lens is continuously repeated at a rate of one thousand times per second while the shutter is open. The performance benefits of using image stabilization can be dramatic. Figures 7 and 8 graphically illustrate the improvement in image quality obtained with the image stabilization system on. Image stabilization allows the user to take comparable quality photographs with the shutter speed approximately four times slower than when the system is off, enabling hand held shots in low light conditions that are not possible otherwise. Some excellent tutorials on image stabilization (or vibration reduction, as called by Nikon) can be found from reference [4].

Figure 7: Fuji S3 Pro / Nikon 24-120mm VR ISO 100 1/4 sec f/16 with vibration reduction OFF

Figure 8: Same conditions but with the image stabilization system turned ON

Since most image stabilization systems implement the controller in software, they can continually update the controller to improve the system performance. Older versions of the image stabilization software had problems when the camera was mounted on a tripod. When the shutter was opened, it introduced a high frequency vibration due to the tripod resonant frequency which is much higher than the camera shake the system was designed to remove. This resulted in very poor image quality. The current VR II system has upgraded sensors and software which can detect the high frequency jitter due to the tripod and can greatly mitigate this effect. The upgrade to the angular velocity sensors also include better low frequency response characteristics to allow greater attenuation of image motion.

Another issue is that the angular velocity sensors have biases which cause the controlling lens to drift over time. As the lens center drifts, it introduces more off-axis aberrations into the image. The Nikon VR II system recenters the lens just prior to shutter release to maximize optical image quality.

5 Summary

Feedback control has long been used in optical systems to improve image quality. Until recently, this use was restricted to large and expensive optical systems where the cost of implementing control systems was required to meet the performance requirements. However, the last decade has seen a revolution in smaller and less expensive sensors and actuators. This, combined with extensive use of powerful digital signal processors that can run real-time, has enabled control techniques to be applied to smaller and much less expensive systems. Image stabilization systems for cameras are just one example of the growing use of feedback control in optical systems.

As advances in MEMS technologies progress and as computing power becomes less expensive, this trend will continue to accelerate. The next decade promises to be an exciting time for the combination of optics and controls as many new applications for optical systems will undoubtedly emerge.

6 References

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