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DESIGN OF ROBUST FEEDBACK CONTROLLERS FOR A LASER BEAM STABILIZER

by

Kwabena A. Konadu

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Department: Mechanical Engineering
Major: Mechanical Engineering
Major Professor: Dr. Sun Yi

North Carolina A&T State University
Greensboro, North Carolina
2012

School of Graduate Studies
North Carolina Agricultural and Technical State University

This is to certify that the Master's Thesis of

Kwabena A. Konadu

has met the thesis requirements of
North Carolina Agricultural and Technical State University

Greensboro, North Carolina
2012

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DEDICATION

I dedicate this Master's Thesis to my parents, my late father, Yaw A. Konadu and my mother, Naomi N. Konadu who have been of great support and inspiration throughout my entire education. I also want to dedicate this work to God for guiding and seeing me through though challenges throughout my Master's Program to make this work a success.

BIOGRAPHICAL SKETCH

Kwabena A. Konadu was born on February 19, 1985, in Tema, Ghana. He received the Bachelor of Science degree in Mechanical Engineering from the Kwame Nkrumah University of Science and Technology in 2007. He is currently a candidate for the Master of Science degree in Mechanical Engineering.

ACKNOWLEDGMENT

I am very grateful to my advisor, Dr. Sun Yi, for his guidance and support through my educational and personally challenging times during my studies at North Carolina Agricultural and Technical State University. I wish to express my appreciation to my thesis committee members, Dr. Mannur J. Sundaresan and Dr. Kim for their time and review of my thesis. I would also like to acknowledge my department chair, Dr. Samuel Owusu-Ofori for his support and encouragement throughout this Master's Program. Lastly, I wish to thank my family and friends for their constant support, encouragement and love.

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LIST OF SYMBOLS

K	Open-loop steady state gain
k_p	Proportional control gain
k_d	Derivative control gain
k_i	Integral control gain
P	Open-loop transfer function
G	Closed-loop transfer function
ω_0	Natural frequency
ω_f	Cut-off frequency
ω_c	Cross-over frequency
ω_{bw1}	First order bandwidth
ω_{bw2}	Second order bandwidth
PM	Phase margin
ζ	Damping ratio
ζ_f	Damping ratio of filter
x	Real state
$\hat{x}$	Observed state
L	Observer gain
p	Pole location of feedback control gain
t `	Pole location of estimator

ABSTRACT

Konadu, Kwabena A. DESIGN OF ROBUST FEEDBACK CONTROLLERS FOR A LASER BEAM STABILIZER. **(Major Advisor: Sun Yi)**, North Carolina Agricultural and Technical State University.

High-precision positioning of laser beams has been one of the greatest challenges in industry due to inevitable existence of disturbance and noise. This work addresses this challenge by employing two different control strategies, namely, Proportional Integral Derivative (PID) and State Feedback with an observer for control. Control strategies are intended to stabilize the position of a laser beam on a Position Sensing Device (PSD) located on a Laser Beam Stabilization (laser beam system) equipment. The laser beam system consist of a laser source, a fast steering mirror (FSM), a position sensing device, and a vibrating platform which generates active disturbances. The traditional proportional integral derivative controller is widely used in industry, due to its satisfactory performance, various available tuning methods and relatively straightforward design processes. However, design of filters to obtain the derivative signal is challenging and the filtering can unexpectedly distort the dynamics of the system being controlled. As an alternative, an observer-based state feedback (OBSF) method is proposed and implemented. This method uses the state-space model of the laser beam system, where all the state variables cannot be measured directly. Therefore, an observer is applied to estimate the state of the system. For observer design, eigenvalue assignment and optimal design methods are used and compared in terms of system performance. Also, comparison between the proportional integral derivative and observer-based state

feedback controllers for laser beam stabilization are provided. Simulations and experimental results of the two controllers show that the observer-based state feedback controller has a faster response, rejects disturbance better and has a straight forward design procedure.

CHAPTER 1

INTRODUCTION

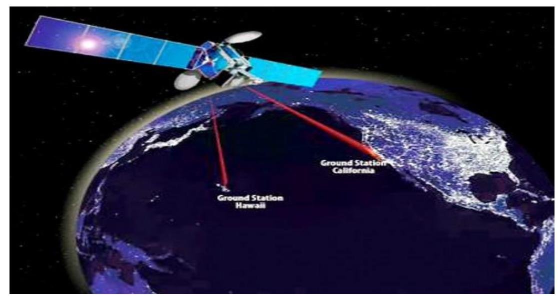
1.1 Applications and Motivation

A laser is a device that works on the principle of quantum mechanics to create a beam of light through optical amplification where all the photons are in a coherent state, usually with the same frequency and phase. The light from the laser is often tightly focused and should not diverge much resulting in the typical laser beam. The term "laser" originated from an acronym for *Light Amplification by Simulated Emission of Radiation*. The operation of the laser is based on the work by Albert Einstein, Alfred Kastler and Theodore Maiman (Duarte 2009; Jones 2012).

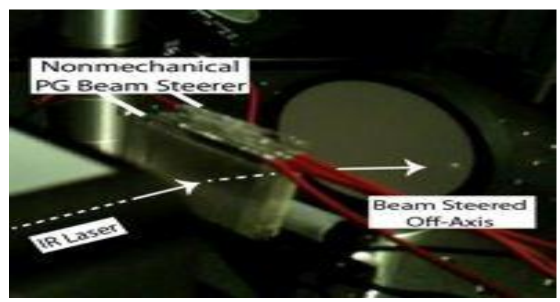
Laser beams are used these days for many purposes, such as communication, transmitting data, surgical purposes, printing, weapon systems, recording and various industrial purposes. Because laser beams have to aim at a target with accuracy and high light intensity level through a transmissible media which it travels while exposed to many forms of disturbances, high precision is required in the applications of laser beams. It is not possible to eliminate such sources of disturbance completely from the medium through which the laser beam travels; therefore, it is important to develop control measures to ensure that the beam aims at the intended target even in the presence of multiple disturbances (Giallorenzi and Limb 2009).

Importance of the control of laser beams and potential industries that will benefit from this research work.

Figure 1.1 show representative examples of industries that utilize laser beams (Duarte 2009; Quanser 2010);



(a) (b)



(c) (d)

Figure 1.1. Applications of Laser Beams, (a) Medical, (b) Military, (c) Industrial Commercial, (d) Electronics & Data Communication (Mead 2009; Escuti 2011)

1. *Medical*: a variety of surgeries are performed by using laser beam systems,
2. *Military*: most firearms applications use laser beam systems as a tool to enhance the targeting of weapon systems and a target designator in aircraft,

3. *Industrial and commercial*: cutting, preening, welding, marking of metals and other materials are done by using laser beam systems,
4. *Electronics and data communications*: laser beam systems are used for optical communications over optical fiber and free space as well as storage of data in optical discs. Also, applications include nuclear fusion, microscopy, laser cooling, material processing, photochemistry, etc.

Some advantages of laser optical systems over other systems in free space are (Arnon and Kopeika 1997):

i. smaller size and weight,
ii. less transmitter power,
iii. larger bandwidth, and
iv. higher resistance to interference.

The accurate pointing of the laser beam is a big and complicated challenge for successful operation of these systems due to difficulty in aiming the laser beam on the intended target, narrow beam divergence angle and vibration of the pointing system. Such vibrations of the transmitted beam are caused by auxiliary devices such as fans, external light sources from fluorescents, computers, pumps and any device that introduces high-frequency signals to the system. These vibrations introduce error into the system and have the effect of deviating the laser beam from its accurate intended target. The aim of this thesis work is to design controllers that will correct or minimize dynamic laser beam pointing errors in analytical ways. The controllers are validated through simulations and experiments.

1.2 Operating Principle of a Laser Beam Control System

In most laser beam control systems, deviations between the beam position and the intended target is corrected or stabilized using an actuator in a form of fast acting mirrors. This error information fed to the controller in the form of feedback by sensors such as Position Sensing Devices (PSD), quadrant-photo detectors and photodiode sensors. These sensors are used to determine the beam position and light intensity (Arancibia, Gibson et al. 2004).

A traditional control system operation of a laser beam is demonstrated in Figure 1.2. The effect of the disturbance appears to have magnified on the target. When the system is in operation, the laser beam comes from the source to the Fast Acting Mirror (FAM) which is reflected through a glass splitter to the target.

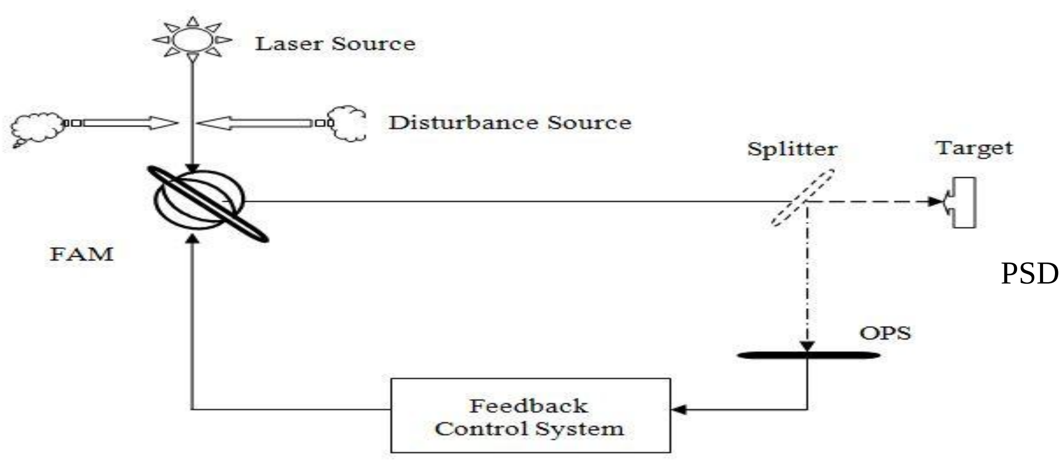


Figure 1.2. Operating Principle of the Control System of a Laser Beam

This glass splitter refracts a small percentage of the beam to a position sensing device. The position sensing device measures how far the beam has been displaced from the target and sends feedback to the control system. The control system then sends signal to steer the FAM / actuator such that the beam remains stable on the target (Arancibia, Gibson et al. 2004; Ying, Hanqi et al. 2005; Quanser 2010).

1.3 Beam Stabilization: Theoretical Background

Applications normally require high accuracy of the beam positioning. The laser systems require precision control in tracking and pointing of the target. Furthermore, this precision must be maintained over sustained periods of time. Further research work has been done on the subject to note the extent of work that has been done by other researchers on the matter.

Techniques to address the problem using passive approaches are presented in (Zia 1992; Bodson, Sacks et al. 1994; Glaese, Anderson et al. 2000), there; both feedback and adaptive feed-forward control techniques were implemented using two actuators (a fast steering mirror and a secondary acoustic speaker located near the precision mirror) for reducing an acoustically induced jitter. The actuator consists of a flexure-mounted mirror exposed to an acoustic field that generates disturbance to the beam.

Another approach is the implementation of an adaptive controller that applies recursive least squares (RLS) algorithm to predict dominant output disturbance frequencies and dynamically computes control commands to minimize the output error. Such methods are presented in (Arancibia, Gibson et al. 2004; Chi-Ying, Yen-Cheng et al. 2008; Richard T. O'Brien and Watkins 2011; Tsu-Chin, Gibson et al. 2011).

The third method considers the implementation of passive and active vibration isolator which reduces the transmission of vibrations from the system to the target presented in (Arnon and Kopeika 1997). The passive isolator includes a mechanical low-pass filter of a spring-mass system whiles the active isolator includes a vibration-control system, force actuators, and displacement sensors. The passive isolator reduces high frequency vibration disturbances in which the ability of disturbance rejection of the fine pointing mechanism is not sufficient. The active isolator dampens low-frequency, high amplitude vibrations (Jong-Shik, Chung Choo et al. 2006; Chang and Liu 2007).

The problem has also been investigated in (Knibbe 1993; Perez-Arancibia, Gibson et al. 2009), by utilizing mechanical techniques for nutation. Known amount of tracking error is introduced into the system by introducing high frequency nutation signals. This is used to determine the position of the laser beam. This approach requires high sampling rates if it is being implemented in discretized form.

The fifth technique is the self-tuning feed-forward jitter-rejection method, presented in (Arnon and Kopeika 1997; Horowitz, Li et al. 1998; Hara, Maeyama et al. 2008; Busack, Morel et al. 2010). This method uses a minute accelerometer to observe the vibration characteristics. The propagating signal of the vibration and disturbance are monitored and electrically compensated for before they affect the communication system. Implementation of this model in a practical system is not straightforward because (Arnon and Kopeika 1997; Skormin, Tascillo et al. 1997):

i. The disturbance should be monitored along three orthogonal axes.

ii. The complex mechanical configuration of the optical system causes the disturbance-compensation signal to be defined as a linear combination of all three orthogonal disturbance components.

iii. The transfer function of the accelerometer must be stable at all times even when environmental conditions change.

An alternate approach is demonstrated in (Ming-Yuan and Li 1995; Li, Chang et al. 2001; Ying, Hanqi et al. 2005; Kwabena A. Konadu and Yi 2011; Landolsi, Dhaouadi et al. 2011). A proportional-integral- derivative (PID) controller is implemented together with a beam-stabilized optical switch to stabilize a beam at a desired angle to maximize the optical power detected by a photodiode using a voice-coil motor actuator. Results prove the proportional integral derivative controller to be an effective method of stabilizing the laser beam with minimal switching time. proportional integral derivative controllers are still the most widely used in the application industry because it has alternative tuning methods (Precup and Hellendoorn 2011), It is affordable with simple structures, and offer satisfactory control system performance.

A seventh method is the implementation of a kalman filter (Yokoyama, Nagasawa et al. 1994; Perez-Arancibia, Gibson et al. 2009; Kwabena A. Konadu and Yi 2011). In this approach, an extended kalman filter (EKF) is used to estimate the position of the laser beam center using the intensity measurement obtained from a single photodiode sensor. The estimated coordinates are used to generate a control signal by means of a pair of single-input/single-output (SISO) and linear time-invariant (LTI) controllers (Chang and Liu 2007). These controllers maximize the light intensity detected by the photodiode sensor, which is equivalent to the particular location of the laser beam center. The EKF is not an exact solution, thus a heuristic solution, and there is no assurance of functionality or optimal control. Results presented in (Perez-Arancibia, Gibson et al. 2009) suggest that it is not possible to steer the system to the desired optimal operating point but an amount of disturbance is shown to be rejected from the system.

Lastly, in order to reduce the effects of noise and disturbances, control strategies for a Laser Tracking System (LTS) that exhibit high precision tracking and measurement performances has been developed in (Leigh-Lancaster, Shirinzadeh et al. 1997; Li, Chang et al. 2001; Ying, Hanqi et al. 2005), using fuzzy logic controllers. This uses distance reading feedback from a laser interferometer and off-centered distance error feedback measured by a four-quadrant photo detector (Ming-Yuan and Li 1995). This controller minimizes target tracking error and suppress vibration disturbances and coupling effects from external sources mostly in both linear and non-linear systems.

The method considered in this thesis work is the classical proportional integral derivative controller and an Observer-Based State Feedback (OBSF) controller. The design procedure for the proportional integral derivative controller is presented in (Quanser 2010). This method will be followed to design a specific proportional integral derivative controller and implemented on the laser beam system. An alternate control scheme will be designed using the observer-based state feedback method which is the main contribution of this work. This method considers the laser beam system as a plant which is a linear time-invariant (LTI) system with single-input single-output (SISO), and models the system into its state-space form. An observer which receives feedback signal from the plant output is designed to estimate the location of the beam and stabilize it on a position sensing device.

1.4 Laser Beam Stabilization Experiment

Because a laser source produces a laser beam that is dynamically sensitive, the control of these laser beams in all areas of its application and industry is one of the biggest challenges (Arnon and Kopeika 1997). The laser beam stabilization equipment as shown in Figure 1.3 is an experiment designed to help solve the control issue in the areas of application and industries of laser beams. It is used to correct or minimize dynamic laser beam pointing errors in application systems by designing and implementing controllers.

The laser beam system consist of four main components (Quanser 2010):

1. The laser source, a Light Emission Diode (LED) light which produces the laser light during the experiment.
2. A Fast Steering Mirror (FSM) which acts as the actuator. It receives control signal from the controller that will be designed to rotate about its pivot such that incident laser beam on it is reflected directly to the intended target.
3. A Position Sensing Device (PSD) which detects the coordinated position of the laser beam. In this study, the intended target is the center of the position sensing device.
4. A vibrating platform for subjecting the system to active disturbance artificially.

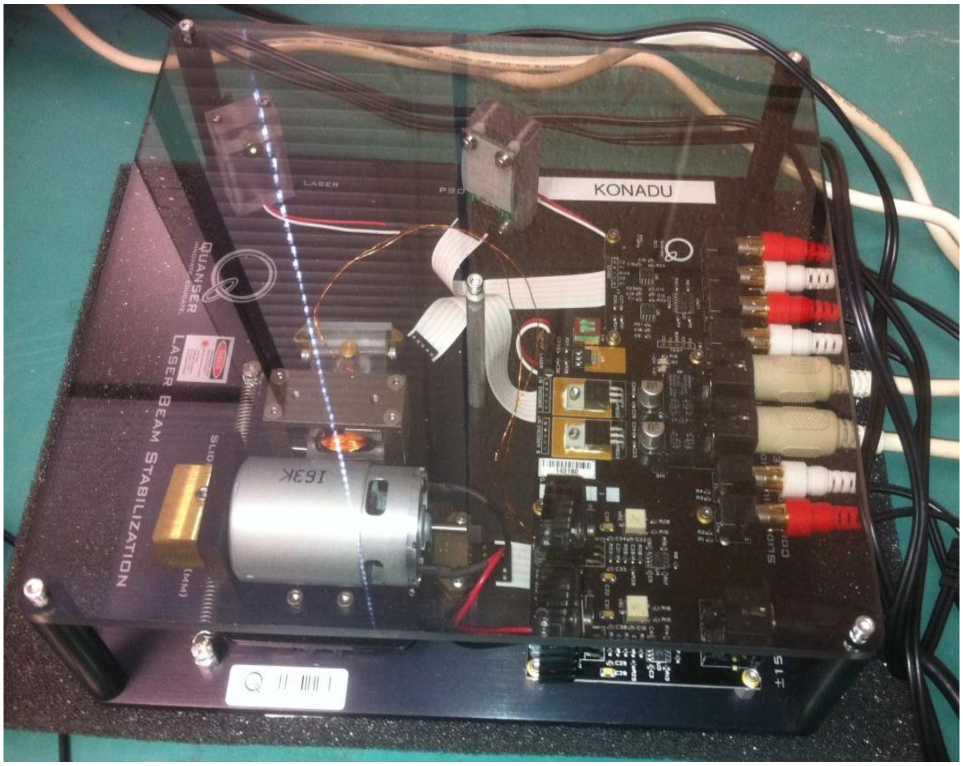


Figure 1.3. Laser Beam Stabilization Equipment

1.5 Objectives

Upon thorough literature review of the stabilization of laser beams by researchers, it has been identified that not much work has been done on stabilizing laser beams using observer-based state feedback (OBSF). Most researchers have looked at the control of laser beams with the other methods (Ying, Hanqi et al. 2005).

The specific objectives of this work are:

1. To design a controller to stabilize a laser beam on a laser beam stabilization equipment using the traditional proportional integral derivative method,
2. To design an alternate controller using an observer-based state feedback method,

3. To compare the controllers in terms of design procedure and effectiveness performance through simulations and experiments, and
4. To determine the most effective controller based on performance.

1.6 Thesis Layout

The rest of this thesis is organized on four main sections with Chapter 2 dedicated to the design of the proportional integral derivative controller. Chapter 3 presents the design of the observer-based state feedback controller. Chapter 4 shows the experimental set-up, presents and discusses simulation and experimental results for the controllers, with the conclusion in Chapter 5.

CHAPTER 2

PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER

2.1 Design of Proportional Integral Derivative Controller

The purpose is to design a proportional-integral-derivative controller (Figure 2.1) that uses all these three terms to compensate for any error recorded by the position sensing device on the target. This controller will determine the right amount of voltage that will steer the actuator in a way that the beam is always reflected directly to the center of the position sensing device even in active disturbance.

The System will utilize an RMS estimator as shown in Figure 2.2 to determine the actual position of the laser on the position sensing device. It will record the deviation of the beam from the middle of the position sensing device (the reference center) and display the value digitally. The aim is to estimate signal values that are close to the theoretical values (Quanser 2010).

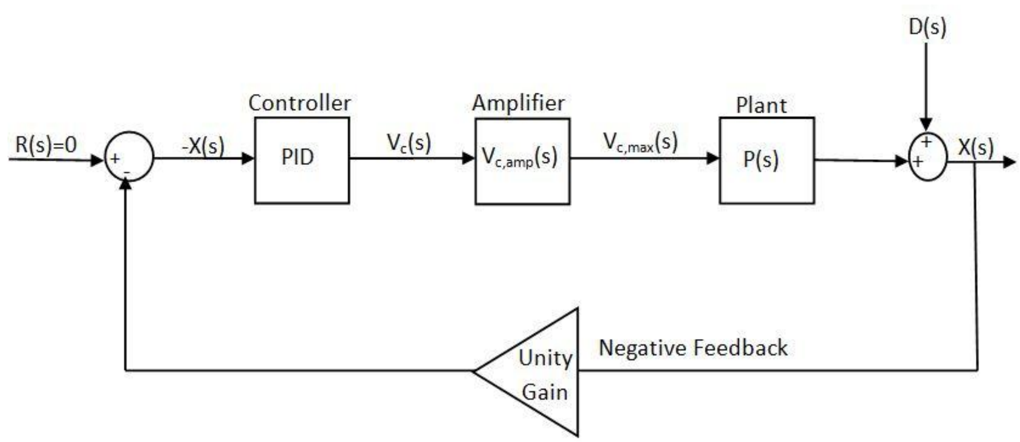


Figure 2.1. Block Diagram of a PID Controller in Closed-loop

The performance of the estimator when tested showed that the effect of noise and disturbance alters the accuracy of its values. A second-order low-pass filter is then introduced in the estimator to reduce these errors.

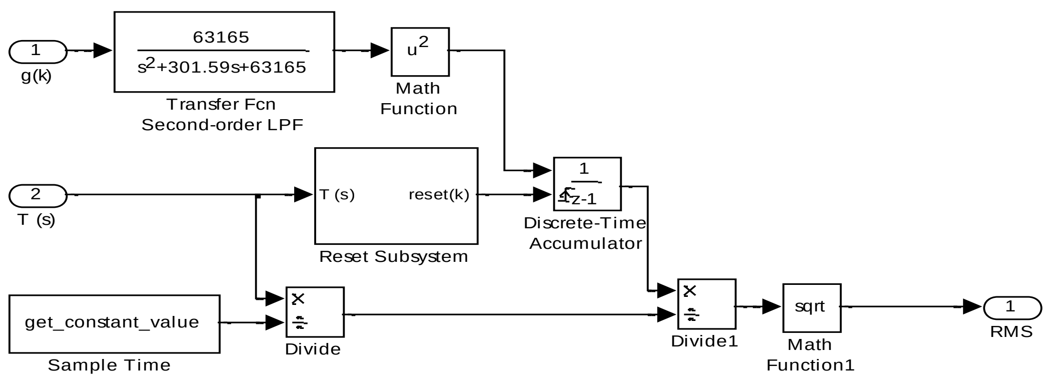


Figure 2.2. RMS Estimator Model with Low-Pass Filter

It is assumed that there is no actuator saturation and amplifier offset,

Thus, $V_{c,amp} = V_c$,

where $V_c(s)$ is the Laplace Transform of the voice-coil digital-to-Analog voltage and $V_{c,max}$ is the maximum voltage that can be supplied to the voice-coil by the power.

2.2 Determining the Transfer Function

The transfer function (T.F.) of the closed loop disturbance-to-position of the system, $G_{x,d}$, is given as; (Quanser 2010) (Chen 1999; Ogata 2002)

$$G_{x,d} = \frac{X(s)}{D(s)} \tag{2.1}$$

where X(s) is the Laplace Transform of the position measured by the position sensing device, D(s) is the Laplace Transform of the disturbance. The laser beam system utilizes the unity negative feedback in the closed-loop system as;

$$X(s) = -P(s)C(s)X(s) + D(s) \tag{2.2}$$

the plant transfer function is;

$$P(s) = \frac{K}{s(\tau s + 1)} \tag{2.3}$$

the proportional integral derivative controller, C, is given as;

$$C(s) = k_p + k_d s + \frac{k_i}{s} \tag{2.4}$$

where k_p is the proportional control gain, k_d is the derivative control gain and k_i is the integral control gain. Equations (2.2), (2.3) and (2.4) are substituted into equation (2.1) to obtain the closed loop transfer function, $G_{x,d}$, as;

$$G_{x,d} = \frac{s^2(\tau s + 1)}{s^3\tau + (1 + Kk_d)s^2 + Kk_p s + Kk_i} \tag{2.5}$$

2.3 Determination of the Control Gains

For the Ideal proportional integral derivative gains, the denominator of equation (2.5), (closed-loop transfer function) is compared with the third-order characteristic Equation below;

$$(s^2 + 2\zeta\omega_0 s + {\omega_0}^2)\,(s + p_0) \tag{2.6}$$

where p_0 is the zero location. Comparing the coefficients in Equations (2.6) to the denominator of equation (2.5) yields the control gains;

$$k_p = \frac{\omega_0(\omega_0 + 2\zeta p_0)\tau}{K} \tag{2.7}$$

$$k_i = \frac{{\omega_0}^2 p_0 \tau}{K} \tag{2.8}$$

$$k_d = \frac{2\zeta\omega_0\tau + p_0\tau - 1}{K} \tag{2.9}$$

2.3.1 Determination of the Natural Frequency

The natural frequency of the laser beam system is obtained by substituting the gains and parameters of the proportional integral derivative specification into the closed-loop transfer function equation to obtain the frequency response of the system. The natural frequency is found from the magnitude of the frequency response as (Quanser 2010):

$$\omega_0 = \frac{\sqrt{-\tau\left|G_{x,d}(\omega)\right|\omega\left(\omega\tau\left|G_{x,d}(\omega)\right| - \sqrt{\omega^2\tau^2 + 1}\ \right)}}{\tau\left|G_{x,d}(\omega)\right|} \tag{2.10}$$

Substituting the specified damped frequency, the system gain, and time constant into equation (2.10) yields the natural frequency, $\omega_0 = 562.703 \approx$ 563 rad/s. Hence, the natural frequency, ω_0 of the system is obtained as 563 rad/s.

2.3.2 Specifications of Proportional Integral Derivative Controller

1) The damping ratio of the ideal proportional integral derivative controller is set to $1\ (\zeta = 1)$. Thus, the controller is critically damped and does not add any oscillations to the system.

2) The closed-loop gain should not exceed 0.05; $\left|G_{x,d}(\omega_d)\right| \leq 0.05$. The gain of the system, is the ratio of position measured on the position sensing device to the

disturbance given as; $\left|G_{x,d}(\omega_d)\right| = \frac{x}{d}$.

3) The disturbance frequency, $\omega_d \leq 24\pi$.

4) The zero pole-location specification, the third pole, p_0 is at -0.5.

Substituting the closed-loop system specification parameters into the gain Equations, the ideal closed-loop proportional gain, k_p, is $0.7209 V/mm$, the derivative gain, k_d, is 0.0021 $V.s/mm$, and the integral gain, k_i, is 0.3598 V/mm/s

2.3.3 Practical Proportional Integral Derivative Gains

Because the laser beam system is prone to capturing noise, these noise turns to magnify after taking the derivative of the signal. It is important to include a filter in the design to remove this noise from the system. In this design of practical proportional integral derivative controller, a filter (Low-pass filter) is used to obtain the displacement of the PSD signal.

2.3.4 Specifications of Filter

The transfer function of the second-order band-pass filter is of the form (Ogata 2002; Quanser 2010):

$$H_{xf,x}(s) = \frac{{\omega_f}^2}{S^2 + 2\zeta_f \omega_f s + {\omega_f}^2} \tag{2.11}$$

ω_f is the cut-off frequency and ζ_f is the damping ratio of the filter. The bandwidth ω_{bw2} is obtained from equation (2.12)

$$\omega_{bw2} = \sqrt{2{\zeta_f}^2 + \sqrt{2 - 4{\zeta_f}^2 + 4{\zeta_f}^4}}\,\omega_f. \tag{2.12}$$

$$\omega_f = 10\ \omega_0 = 5627.03\ rad/s$$

The cut-off frequency of the filter is chosen 10 times the natural frequency of the system to allow enough signal to pass through.

The cross-over frequency ω_c is the frequency at which the magnitude of the Transfer Function is 1 or 0 dB. The cross-over frequency, ω_c, is obtained from the magnitude of frequency response as;

$$\omega_c = \sqrt{2 - 4{\zeta_f}^2}\,\omega_f. \tag{2.13}$$

The phase margin (PM) is the amount of phase that exceeds -180 degree at the cross-over frequency, and it's a measure of stability of the system.

Table 2.1. Filter Specification

Filter parameter	**Specification**
Filter bandwith	ω_{bw1} *is given as* $5627.03\ rad/s$
	$\omega_{bw2} > 1.2\ \omega_{bw1}$ $1.2\ \omega_{bw1} = 6752.436\ rad/s$
Phase margin	$PM > 75\ [deg]$
Cut-off frequency	$\omega_f = 10\ \omega_0$

2.3.5 Selected Filter Parameters

Figure 2.3. shows a set of filter parameters for different damping ratios. The parameters are compared with the specifications to find the set that best meet the given requirement. The white markers show the parameters for corresponding damping ratios that are rejected and the black markers are filter parameters for corresponding damping ratios that meet the requirements.

From Figure 2.3., the damping ratio that results in a bandwidth greater than 6752 rad/s and a phase margin greater than 75 degrees is determined as 0.5 and 0.6 but a damping ratio of 0.5 is selected as the choice for designing the filter because its phase margin is closer to the desired specification.

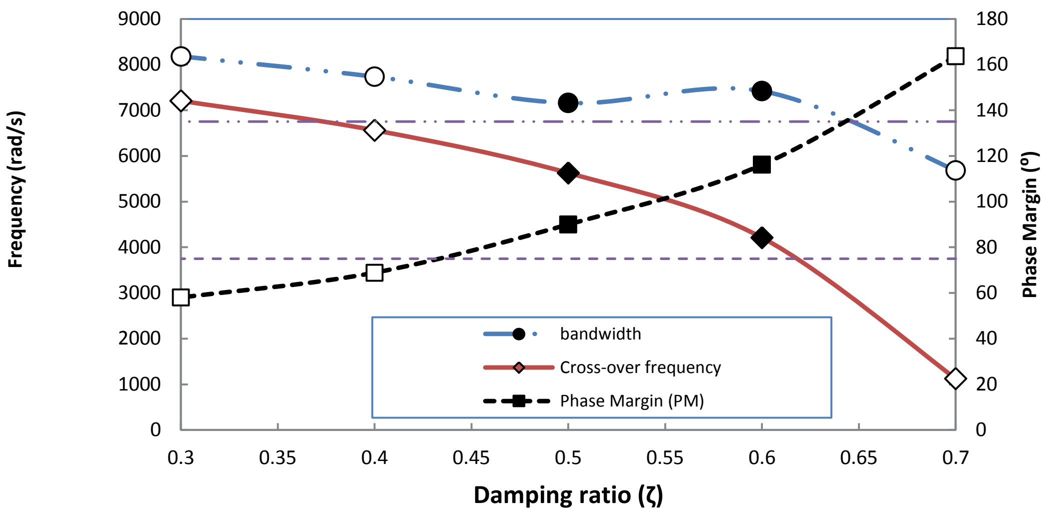


Figure 2.3. Plot of Filter Specifications against Damping Ratio

2.4 Building the Controller

The filter with its desired parameters has been selected, now, the proportional integral derivative controller is built in simulink and its performance is tested to determine if the specified design requirements are met. Figure 2.4. shows a block diagram of the designed laser beam controller. The proportional integral derivative gains after applying the low-pass filter is: k_p = 0.722 V/mm; k_d = 0.002 V.s/mm; k_i = 0.360 V/mm/s.

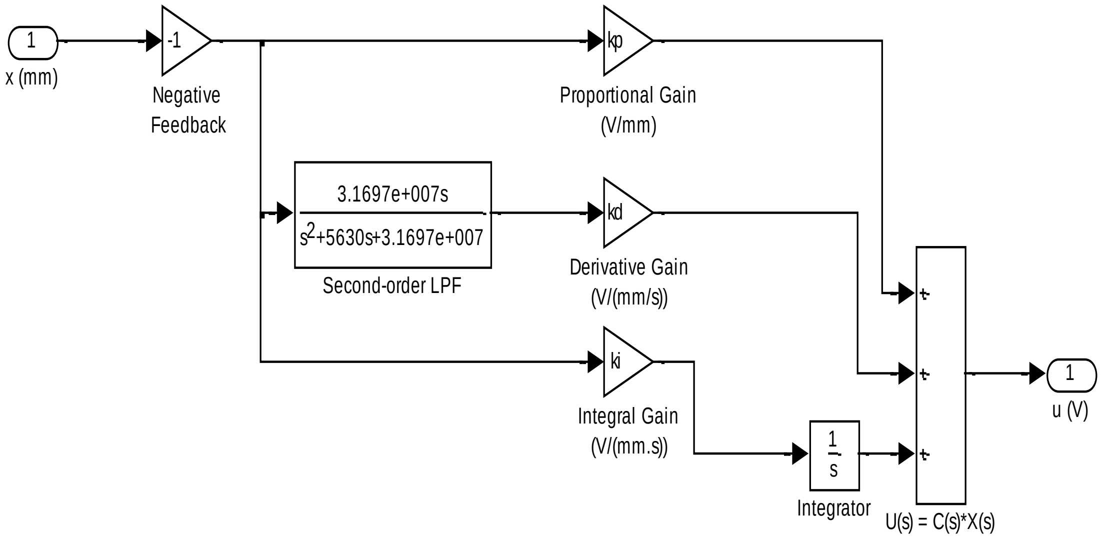


Figure 2.4. Block Diagram of the Proportional Integral Derivative Controller

The gains, k_p, k_d, k_i are placed in the proportional gain block, integral gain block, and derivative gain block shown in Figure 2.4. The low-pass filter is placed in the filter block and simulations are performed to test if results are satisfactory, before experiments are performed.

CHAPTER 3

OBSERVER-BASED STATE FEEDBACK CONTROLLER

3.1 Design of State Observer

Alternatively, Figure 3.1 shows a block diagram of the laser beam stabilization equipment that utilizes an observer-based state feedback for control. The laser beam stabilization equipment is assumed to be a plant and modeled in its state space form and as a linear time-invariant (LTI) system with single-input single output (SISO). It is assumed that;

1) Not all the state variables, x, of the laser beam system are available for measurement.
2) There is not enough sensors, and it is very expensive to obtain all the physical initial conditions, $x(0)$, for the laser beam system.
3) There is an amount of error due to estimation.

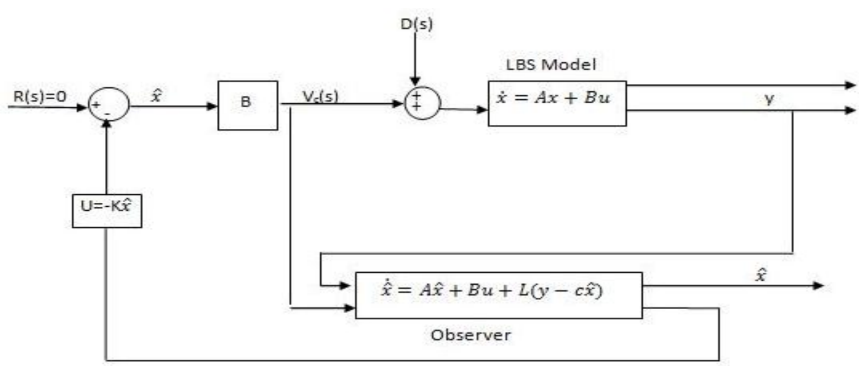


Figure 3.1. Block Diagram of Closed-loop State Feedback Observer

Because information about the dynamics of the system is limited, the design of an observer that computes an estimate of the entire state vector with limited information from the output of the plant for control is proposed.

3.2 Modeling of Laser Beam System and Observer

To obtain the dynamics of the system, the laser beam system is modeled in the state space form as (Franklin, Powell et al. 1995; Ogata 2002);

$$\dot{x} = Ax + Bu \tag{3.1}$$

$$y = Cx \tag{3.2}$$

where A and B are system and input matrices respectively, x and u are state vectors, C is the output matrix (Luenberger 1964; Krokavec and Filasová 2007). The observer is constructed from the state space model of the laser beam system dynamics as;

$$\dot{\hat{x}} = A\hat{x} + Bu \tag{3.3}$$

$$y = C\hat{x} \tag{3.4}$$

Where $\hat{x}$ is the estimate of the actual state, x. Since the exact initial condition, $x(0)$ of the laser beam system is not available, the observer will be used to provide that information. However, the observer gives estimated but not exact information about the system, therefore a continuous increase in error may occur if a poor estimate for $x(0)$ is made. This may result in the observer providing erroneous estimates about the true state of the laser beam system. Error introduced, e, is (Franklin, Powell et al. 1995; Zhou, Doyle et al. 1996);

$$e \cong x - \hat{x} \tag{3.5}$$

This error in estimation can be eliminated very fast by controlling the estimator with error feedback. Thus, the difference between the actual laser beam system outputs and the estimated outputs, are taken and fed back into the observer to compensate for this error as shown in Figure 3.2. (Franklin, Powell et al. 1995; Ogata 2002)

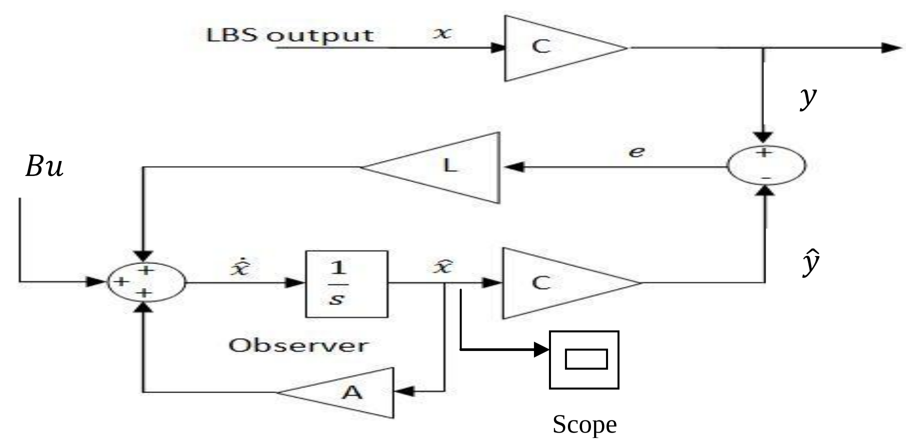


Figure 3.2. Block Diagram of Observer Using Error Feedback for Compensation

The difference in actual output and estimated output can be written as;

$$Cx - C\hat{x} \tag{3.6}$$

Adding the error to the observer gives;

$$\dot{\hat{x}} = A\hat{x} + Bu + L(Cx - C\hat{x})$$

Where L, is the observer gain. The dynamics of the observer can be re-written to include the error to obtain;

$$\dot{\hat{x}} = A\hat{x} + Bu + L(y - C\hat{x}) \tag{3.7}$$

3.3 Determining the State Space Model

The plant transfer function for the laser beam is given in equation (2.3) where K, the open-loop steady state gain, is 2200mm/(V.s) and τ, the open-loop time constant, is 0.005s;

$$\frac{X(s)}{V_c(s)} = \frac{2200}{(0.005s^2 + s)} \tag{3.8}$$

$X(s)$, is the position measured by the position sensing device and $V_c(s)$, is the amount of voltage that enters voice coil actuator. Taking the Laplace inverse of equation (3.8), the equation of motion of laser beam system is obtained as;

$$\ddot{x} = 440000\,V - 200\dot{x} \tag{3.9}$$

From the equation of motion, the System matrix A, and Input matrix B is derived as;

System Matrix $A = \begin{bmatrix} -200 & 0 \\ 1 & 0 \end{bmatrix}$

Input Matrix $B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$

Output Matrix $C = [0 \quad 440000]$

Control Matrix $D = [0]$

Writing the equation of motion in state space equation of the laser beam system can be written as:

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} = \begin{bmatrix} -200 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} U \tag{3.10}$$

where x_1 is the displacement and x_2 is the velocity of the beam

3.3.1 System Controllability

The controllability of the system can be obtained from the laser beam system state space model and used to determine if it is possible for the system to be controlled. The model of the system will have to be changed or altered if the state space equation (23) tends to be uncontrollable.

The first step to determine if the system is controllable is to compute the controllability matrix (Haddad and Bernstein 1992; Chen 1999). The controllability matrix, C_r is derived from Matlab using the command "ctrb (A, B)". The controllability matrix is obtained as (Zhou, Doyle et al. 1996):

$$C_r = \begin{bmatrix} 1 & -200 \\ 0 & 1 \end{bmatrix}$$

Let $v_1\ and v_2$ be vectors of columns 1 and 2 of matrix C_r respectively. If $\alpha_1\ and\ \alpha_2$ are scalar, then (Chen 1999), (Franklin, Powell et al. 1995), (Ogata 2002)

$$\propto_1 \times v_1 + \propto_2 \times v_2 = 0$$

$$Iff\ \ \propto_1 = \propto_2 = 0$$

Then $v_1\ and\ v_2$ are linearly independent of each other, therefore columns 1 and 2 of the controllability matrix are linearly independent. Thus the rank of the controllability matrix is 2. Since the size of the state vector is 2 and the rank of the controllability matrix is 2, then the system is controllable.

3.3.2 System Observability

The Observability of the system can be obtained from the laser beam system state space model and used to determine if the state of the system can be observed if an estimator is designed. Observability matrix, O_v is derived from Matlab using the command “obsv (A, C)”. The observability matrix is obtained as:

$$O_v = \begin{bmatrix} 0 & 440000 \\ 440000 & 0 \end{bmatrix}$$

Columns 1 and 2 of matrix O_v are linearly independent. Thus the rank of the observability matrix is 2. Since the number of rows of the state matrix is 2, and the rank of the observability matrix is 2, then the system is observable.

3.4 Feedback Control Design

For the system to achieve desired response, poles are selected so that the system response to disturbance is dominated by the dynamic characteristics of the observer and not the control law.

Pole placements are locations in the closed-loop system where desired response is achieved when control effort is applied. The location of the poles correspond directly to the eigenvalues of the system, thus, the eigenvalues control the characteristics of the response (Franklin, Powell et al. 1995; Ogata 2002). If the selected poles are not desirable it will require a larger effort to control the system making the design expensive (Franklin, Powell et al. 1995).

The pole locations of the system are obtained from the denominator of the closed-loop response equation by finding the characteristic roots or eigenvalues of the characteristic equation. The equation for the closed loop response is given as (Quanser 2010):

$$G_{x,d} = \frac{s(\tau s + 1)}{s^2\tau + 2\zeta\omega_0\tau s + {\omega_0}^2\tau} \tag{3.11}$$

Substituting the time constant and natural frequency into the denominator of equation (3.11) gives:

$$(0.005)s^2 + (2.547)s + 1297.44 = 0$$

$$s_{1,2} = -254.7 \pm 441.15i$$

Thus the desired poles are obtained as

$$p_1 = -254.7 - 441.15i,\; p_2 = -254.7 + 441.15i$$

3.5 Pole Placement Design of Observer

The control gain K, is derived from Matlab using Ackermann command in equation (3.12) :

K=acker(A,B,p) (3.12)

A is the system matrix, B is the input matrix, and p is desired pole location

The observer is designed to regulate the laser beam by estimating the state of the laser beam system. Two techniques are considered in designing the observer; the Ackermann method which designs the observer without considering uncertainties from the process and sensors. Alternatively, the Kalman method considers the uncertainty and optimally designs a Robust Observer (RO) the laser beam. Simulations and experiments are used to compare these methods.

The Estimator Gain, *L*, is obtained from the Ackermann formula using the Matlab command in equation (3.13):

$$L' = \text{acker}(A', C', t)' \quad (3.13)$$

Where ' denotes the transpose of system matrix and the output matrix respectively. t is desired observer pole location. For a faster decay of the estimator error, the desired estimator Pole location t, is chosen by a factor of 5 (Franklin, Powell et al. 1995; Zhou, Doyle et al. 1996; Ogata 2002):

$$t_1 = -1273.5 - 2205.8i,\ t_2 = -1273.5 + 2205.8i$$

The observer gain, L is:

$$L = \begin{bmatrix} 13.677 \\ -0.005 \end{bmatrix}$$

3.6 Optimal Design of Robust Observer

The design of the observer using the Ackerman formula does not provide robust estimation in the presence of noise in the system. Observer design through the Ackerman formula can make the estimator unstable and inaccurate because this system does not recognize the disturbance from the process and noise from the position sensing device. Thus, the estimated state will diverge from the real state if disturbance and noise is introduced into the system (Franklin, Powell et al. 1995; Zhou, Doyle et al. 1996; Ogata 2002).

The Kalman technique is used to design a robust state estimator to generate optimal estimates of the state of the system. The Kalman takes the state-space model of the system where not all outputs are available for measurement and considers all other inputs (noise) as stochastic as shown in Figure 3.3. The method uses known input u, and covariance matrices Qn, Nn and Rn from the process disturbance w, and measurement noise v to compute the optimal estimator gain L. The covariance matrix are;

Qn = E{ww'}, Rn = E{vv'}, Nn = E{wv'}

Where; w and w' are the process disturbance vectors and its transpose respectively, while v and v' denote the position sensing device noise vector and its transpose.

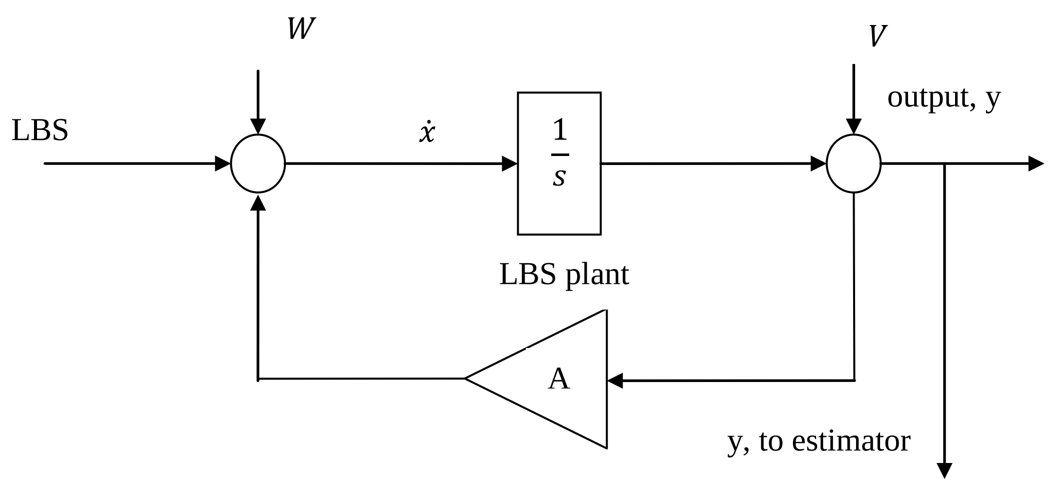


Figure 3.3. Diagram Showing Introduction of Noise and Disturbance on LBS

The laser beam system is assumed to be corrupted by noise (Postlethwaite 1996; Zhou, Doyle et al. 1996). Thus;

$$\dot{x} = Ax + Bu + w \tag{3.14}$$

$$y = Cx + v \tag{3.15}$$

where, w is process disturbance and v is measurement noise from the position sensing device. Rewriting the dynamics of the observer, from equation (3.5), the error in estimation gives;

$$\dot{e} = Ax + Bu + w - A\hat{x} - Bu - L(Cx + v - C\hat{x})$$

$$\dot{e} = (A - LC)e + w - Lv \tag{3.16}$$

Due to the introduction of process and measurement noise into the system, the difference between the real state variable and the estimated state variable will not go to zero. Thus, the error will not approach zero asymptotically, x grows further apart from $\hat{x}$. To ensure that the effect of this error and disturbance on the target remains minimized as possible, the optimal linear quadratic estimator LQE technique using the kalman is used to choose the optimal estimator gain, L.

The optimal observer gain which minimizes this error caused by the process disturbance and measurement noise is:

$$L = PC \times V^{-1} \tag{3.17}$$

where P is the solution of the Algebraic Ricatti Equation (ARE) :

$$PA + AP - PC \times V^{-1}CP + W = 0 \tag{3.18}$$

P, should be a unique positive semi-definite solution of ARE.

C, is the output matrix of the laser beam system, w and v are the disturbance and noise matrix respectively. The optimal choice of L is called the Kalman filter gain and is obtained from Matlab by the command;

[kest,L,P]= kalman(sys,Qn,Rn,Nn) (3.19)

The optimal observer gain, L is:

$$L = \begin{bmatrix} 5.6529 \\ 0.0051 \end{bmatrix}$$

The solution to the ARE is:

$$P = 10^{-3} \times \begin{bmatrix} 0.7025 & 0.0003 \\ 0.0003 & 0.00001 \end{bmatrix}$$

3.7 Building the Controller

Figure 3.4 shows a block diagram of the laser beam system and observer in simulink. Simulations are performed to determine the response of the system when using an observer-based feedback for controlling the laser beam system.

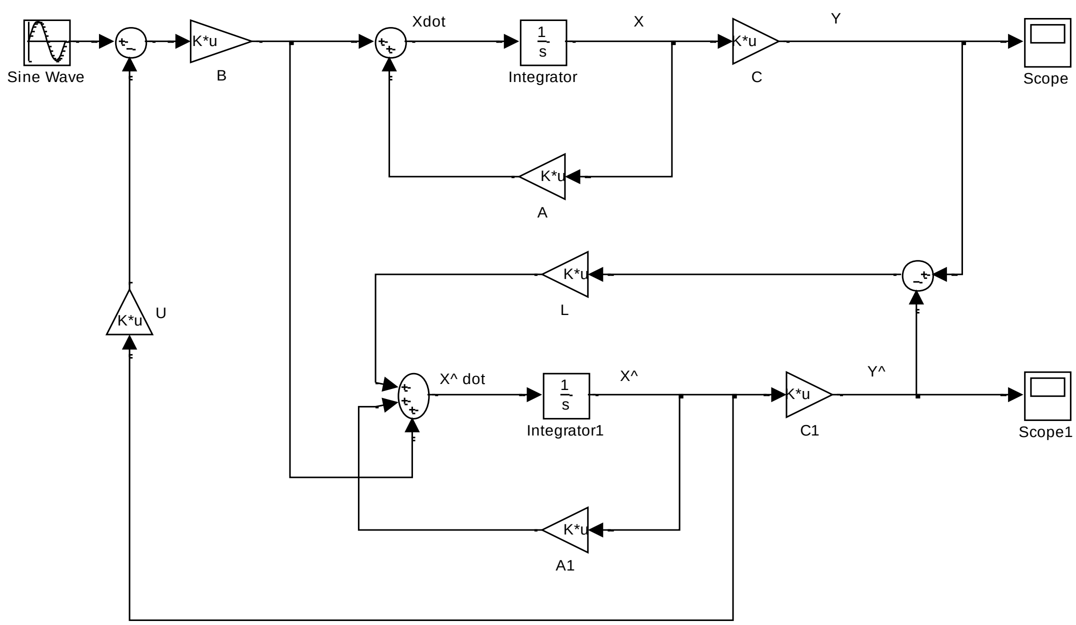


Figure 3.4. Block Diagram of the OBSF Controller

The observer gain, L, and control gains obtained are placed in the observer gain block and control block to test the controller through simulations before experiments are performed.

CHAPTER 4

SIMULATION AND EXPERIMENTAL RESULTS

4.1 Experimental Set-up

The laser beam system experiment shown in Figure 4.1 and Figure 4.2 consist of four main components: PC, laser beam system component, Quanser Personality Intelligent Data (QPID) acquisition board and a Peripheral Component Interconnect (PCI) express board. These are inter-connected and act as a hardware-in-the-Loop (HIL). The PCI board is inserted into the CPU and connected to the QPID terminal board through analog cables. The terminal board is then connected to the laser beam system component through analog and encoder cables before the system is powered. Experiments are run on this system by generating real-time codes from models that runs on a real-time kernel of the processor of the PC. After designing the appropriate controller, the design is built and tested through simulations on the computer.

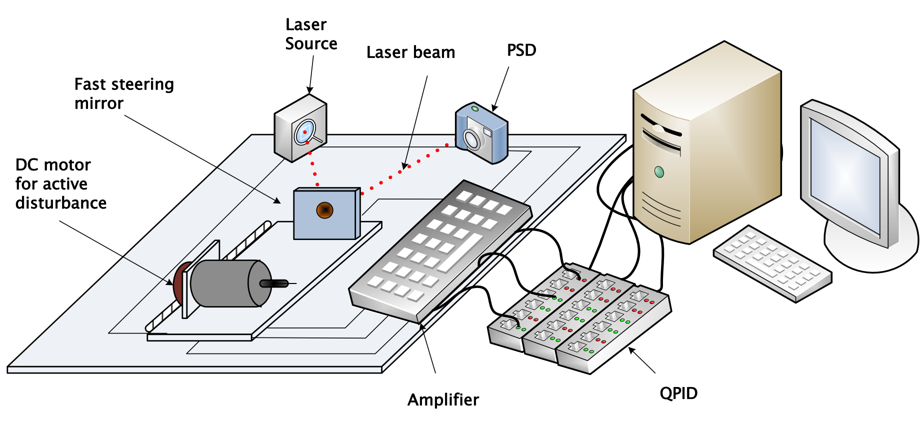


Figure 4.1. Schematic Diagram of a Laser Beam Stabilization Experimental Set-up

The laser beam system platform shown in Figure 4.2 consist of a laser beam from a stationary laser source, an actuator or a FSM which is mounted on a vibrating platform to subject the laser beam to disturbance, a DC motor for subjecting the platform to artificial active disturbance. The amplifier makes sure that the voltage or maximum power that is being supplied to the actuator by the Digital-to-Analog convertor (D/A) is not exceeded and it also magnifies the signal from the position sensing device to the Analog-to-Digital converter. The QPID acts as a data acquisition board and also acts as a digital-to-analog-to-digital convertor (D-A-D), thus it converts the analog position of the laser beam measured by the position sensing device into digital signal for the computer and also converts digitized signal from the designed controller on the computer to analog form for the actuator (FSM). Therefore by using feedback from the position sensing device, controllers are designed to stabilize the vibrations using the FSM as an actuator.

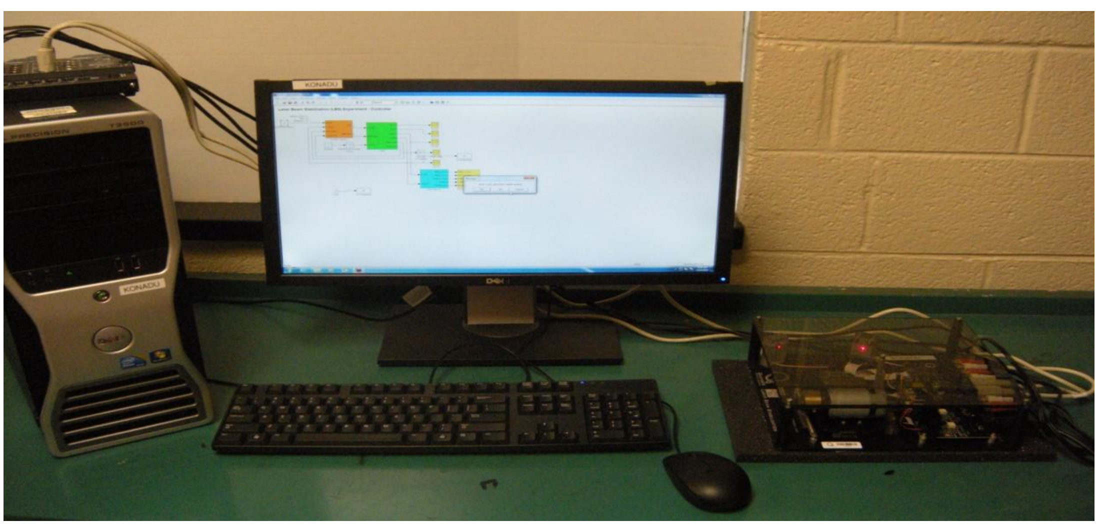


Figure 4.2. Experimental Set-up of the Laser Beam System

The laser beam system is subjected to active disturbance by increasing the disturbance voltage which causes the motor to slide back and forth, thereby displacing the beam from the middle of the position sensing device. The controller intended to stabilize the system is switched on and the response is analyzed.

4.2 Experimental Set-up for Simulations

Before the controller is implemented on the laser beam system, simulations are performed on a virtual laser beam system with specifications and transfer function similar to the real laser beam system to determine if results are satisfactory before replacing the plant with the real laser beam system. This is done to validate the design and prevent any damages to the laser beam stabilization equipment. Figure 4.3 shows a block diagram of the experimental set-up to test the controllers through simulation (Chua, Rainsford et al. 2008).

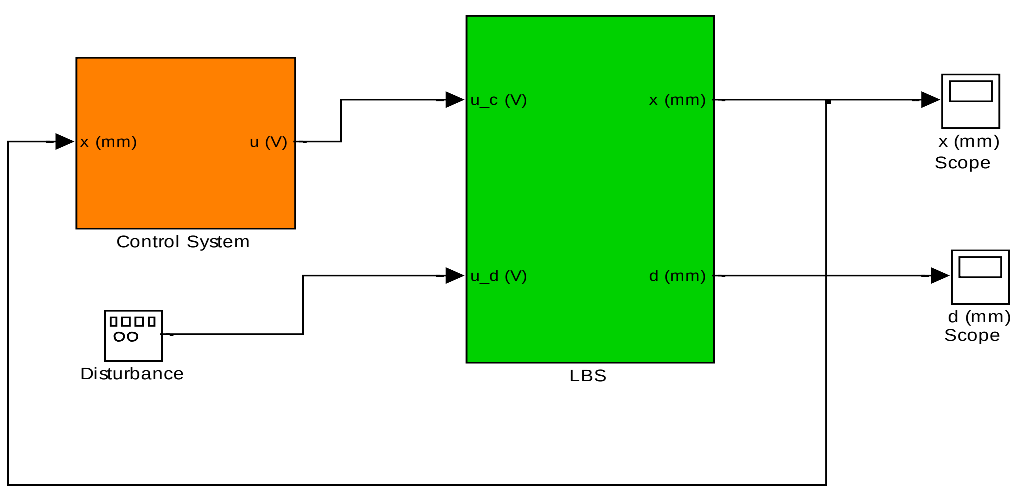


Figure 4.3. Block Diagram of Experimental Setup

This block diagram consist of four main blocks; (1) the Control System Block, which contains the controller, (2) the Signal Generator Block which acts as the motor for subjecting the laser beam system to active disturbance by regulating the frequency and amplitude of the input signal, (3) Plant which acts as the laser beam system shown in Figure 4.4 and (4) the Scope which acts as the position sensing device for detecting the position of the laser beam (x) and the disturbance.

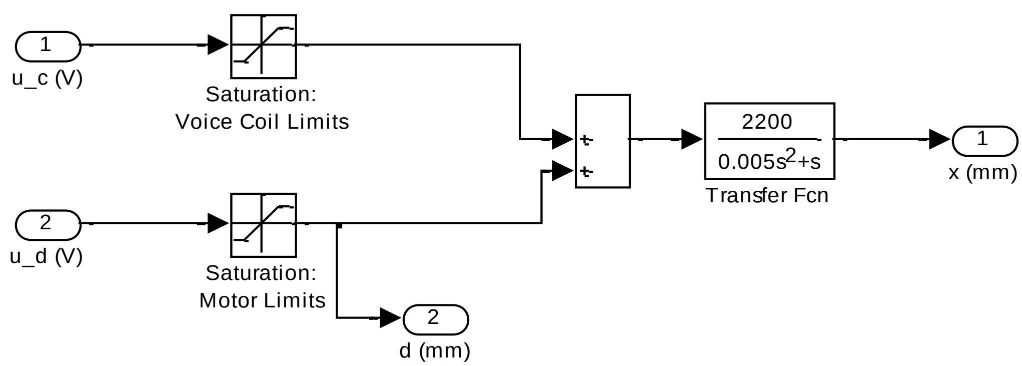


Figure 4.4. Block Diagram of Laser Beam System

This block is designed to have similar specifications to the real laser beam system. The first input port of the laser beam system, U_c recieves signal from the contol system block's output in the form of voltage to control the voice coil actuator. The second input, U_d is the active disturbance from the signal generator's output for subjecting the laser beam to motion. The transfer function and limits are obtained from the real laser beam system, the saturation limits ensures that the amount of voltage that is supplied to the system does not exceed specified or desired limits in order to prevent any form of damage to the equipment.

A block diagram of the observer-based state feedback controller is shown in Figure 4.5. It is assumed that not all the output state variables of the laser beam system can be measured therefore the available output, displacement, is measured by the position sensing device as X(mm). The observer continuously estimates the state of the system based on the output (X) from the laser beam system.

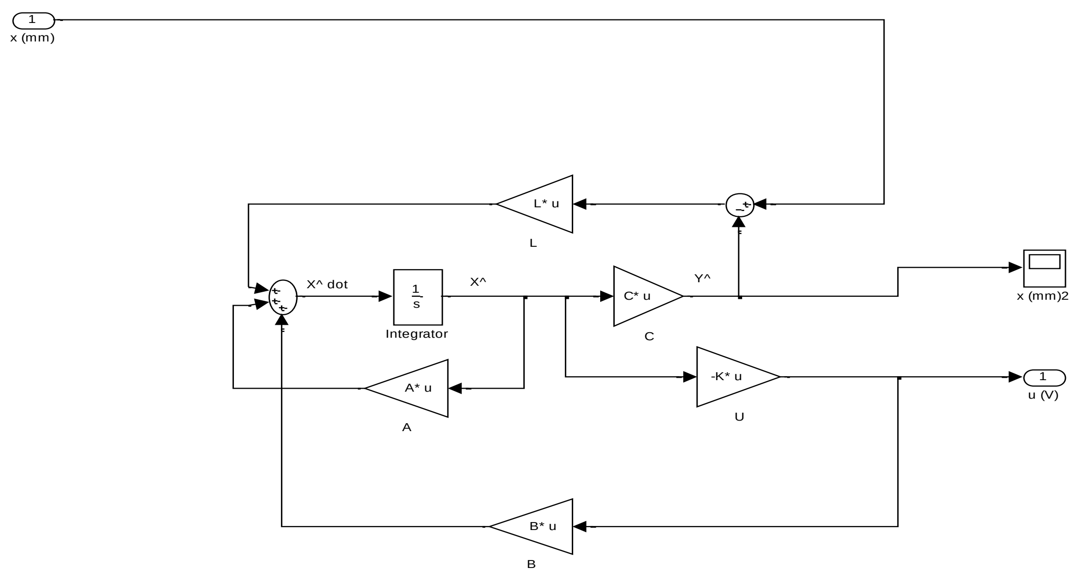


Figure 4.5. Simulation Block Diagram of the OBSF Controller

This estimatator output is U_c, in the form of voltage. The diagram shows the observer gain L, control gain U. System matrix (A), input matrix (B) and output matrix (C) are obtained from the state-space form of the laser beam system.

4.3 Simulation and Experimental Results

To test the peformance of the observer-based state feedback controller, simulations are peformed on the laser beam system(plant) and the response is compared to that using the proportional integral derivative controller to determine whether the results are satisfactory. This is achieved by replacing the control system block in Figure 4.3 with the observer-based state feedback and proportional integral derivative controller shown in Figure 4.5 and Figure 4.6 respectively. The signal generator is set to input a disturbance in a form of a sine wave with a frequency of 12 Hz and an amplitude of 1 mm. Figure 4.7 and Figure 4.8 show the response of the system in using the proportional integral derivative and observer-based state feedback controllers respectively. The response shows that the laser beam vibrates sinusoidally with an amplitude of approximately 350 mm in open loop using the proportional integral derivative controller, however this vibration stabilizes in closed-loop. For the observer-based state feedback controller, the laser beam vibrates with an amplitude of about 350 mm in open-loop and stabilizes about the reference point in closed-loop.

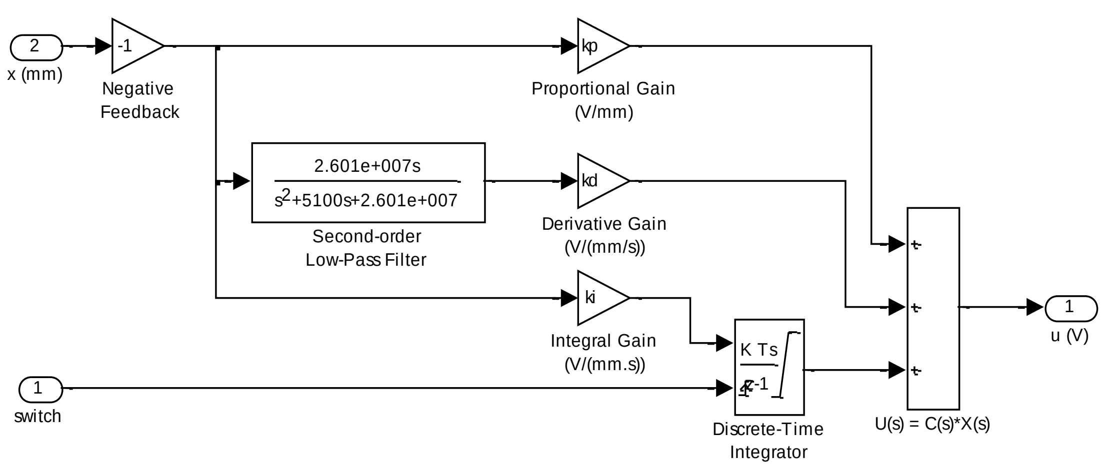


Figure 4.6. Simulation Block Diagram of PID Controller

A comparison of simulation response of the controllers in closed-loop is shown in Figure 4.9. In closed-loop, the response of the observer-based state feedback controller shows that the vibration of the laser beam stabilizes to an amplitude of 2 mm whiles for the proportional integral derivative controller, the amplitude of the laser beam decreases to 1.7 mm.

Both controllers proved to be stable and effective in eliminating the 12 Hz disturbance and significantly stabilizing the vibration of the laser beam. However, the proportional integral derivative controller sustains a relatively smaller amplitude. The results for both controllers are considered satisfactory as shown in Figure 4.9, therefore the peformance of the controllers can be tested on the real laser beam system.

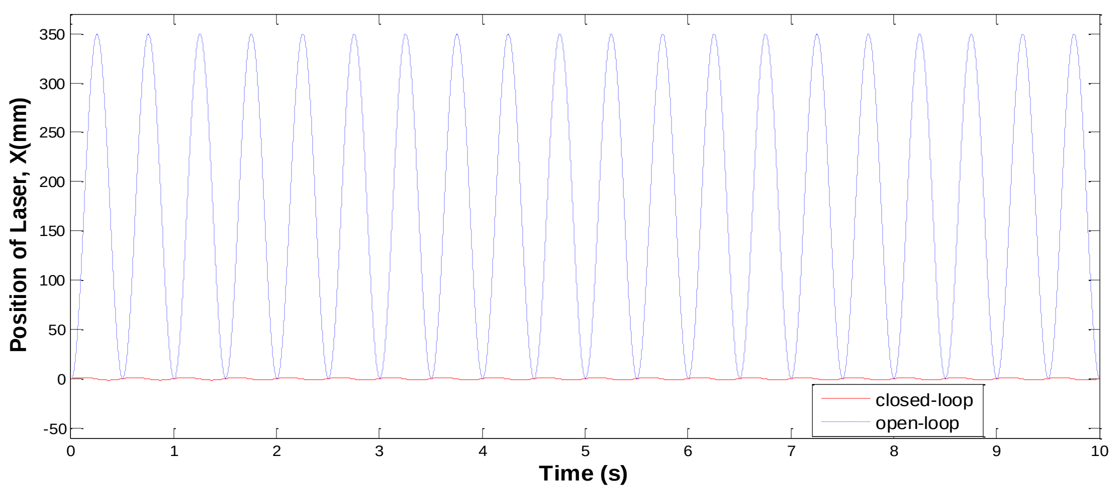


Figure 4.7. Simulation Response of PID Controller

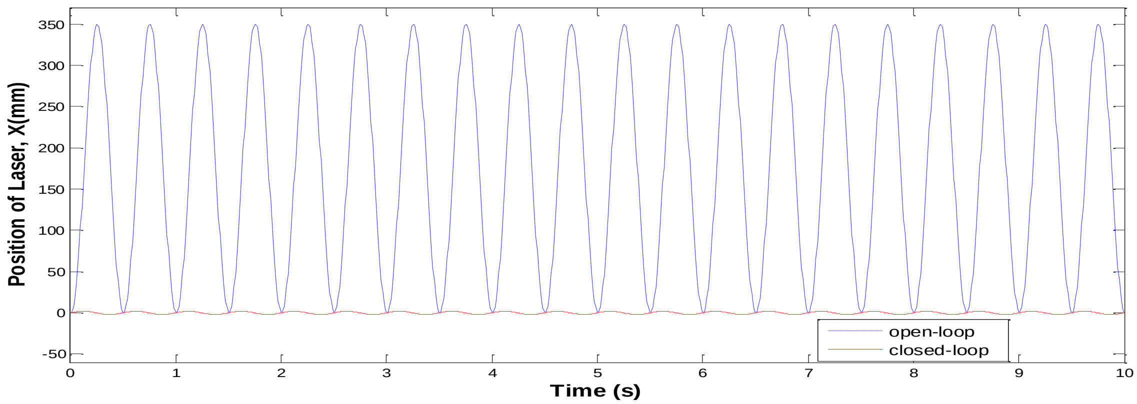


Figure 4.8. Simulation Response of OBSF Controller

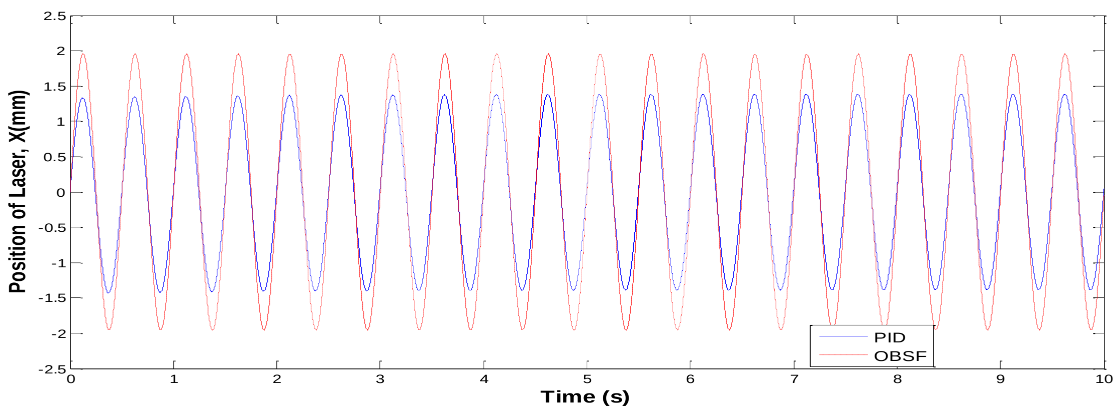


Figure 4.9. Comparison of Closed-loop Simulation Response

4.4 Experimental Results of Proportional Integral Derivative

The simulation response of the laser beam system utilising both controllers gives satisfactory results therefore the laser beam system(plant) is replaced with the real laser beam system to test the actual performance in real time.

After implementing the design on the real system, the controller is tested to determine the closed-loop system gain to confirm if design specifications are met. Figure 4.10 and Table 4.1 shows that the system maintains a desired gain below 0.05 for all disturbance frequencies when the system is switched from open-loop to closed-loop. Hence, the gain requirement is met for this design.

Table 4.1. Disturbance Frequency and System Gain of PID

Disturbance Frequency(Hz)	RMS: d(mm)	RMS: x (mm)	lGx,dl = X/ D
8	0.1468	0.006654	0.045327
9	0.1311	0.005886	0.044897
10	0.1913	0.007179	0.037527
11	0.2865	0.014480	0.050541
12	0.1829	0.007776	0.042515

Figure 4.11 is a plot of the laser beam system in open-loop that is switched to closed-loop after 11.5 seconds. Observation shows that the beam is displaced from the reference point immediately when the controller is switched to closed-loop. This offset however decreases linearly over time and gradually approaches steady state at zero.

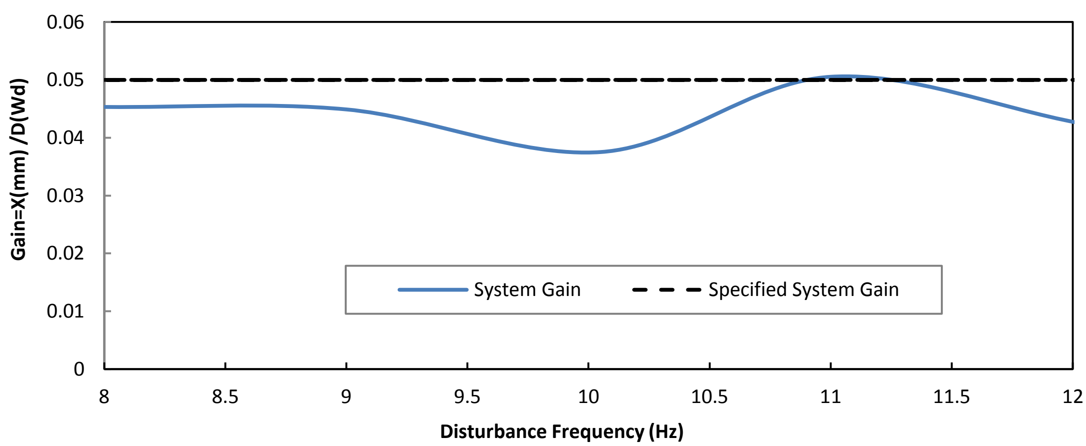


Figure 4.10. Plot of Closed-Loop System Gain against Disturbance Frequency

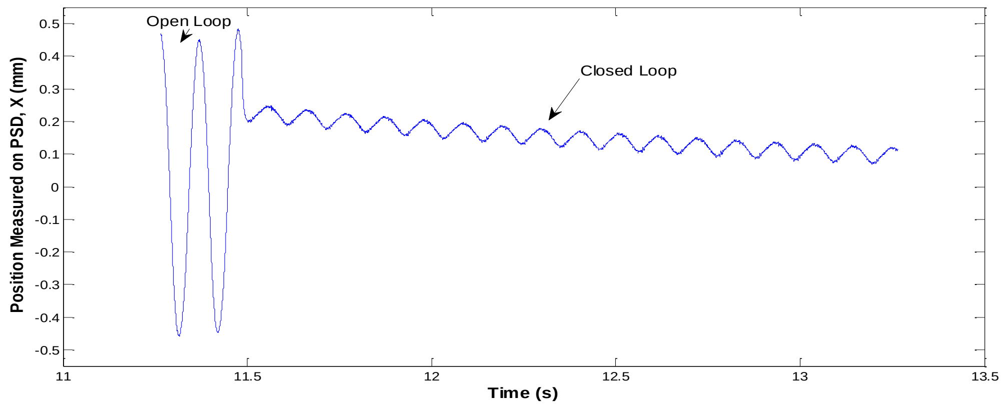


Figure 4.11. Plot of Response for PID Controller

Figure 4.12 shows a Bode diagram for crossover frequencies of the loop transfer function of the controller with a filter. For the signal, the phase margin of the practical loop transfer function has 73.4 degrees.

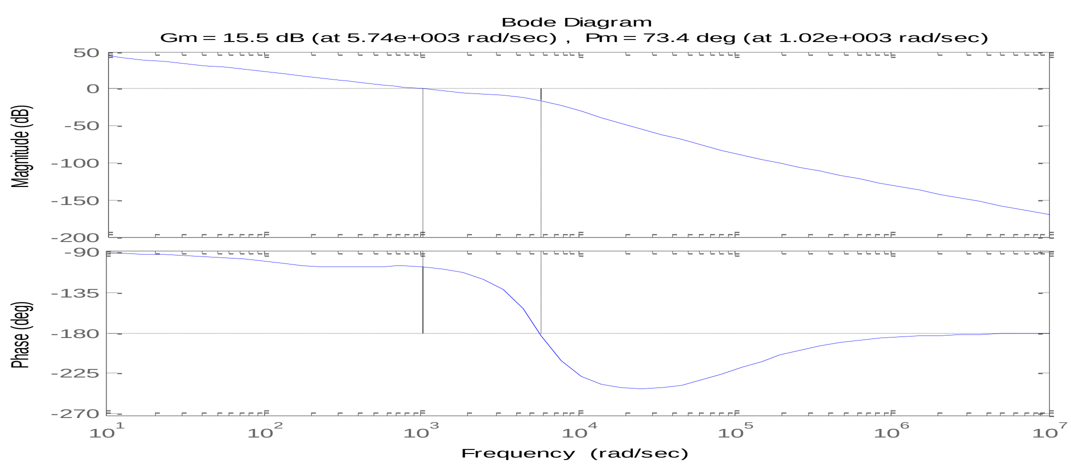


Figure 4.12. Margin Plot for PID Controller

The Phase Margin is the amount of phase that exceeds -180 degree at the cross-over frequency. The more it exceeds -180 degrees, the more stable the system is. The bode diagram shows the PM for the transfer function of the loop. The introduction of filters and sampling has an effect of delay and shift in the stability of the system. A sampling interval is selected such that the stability of the system is not affected.

Although the phase margin is not close to 90 degrees (ideal), the system is still considered to be stable because it is greater than the desired PM of 60 degrees. The reduction in phase margin can be accounted for as the effect of the filter. Figure 4.13 shows that after sampling, the phase margin has reduced to 67.5 degrees meaning the stability of the system has reduced. Even though there is a reduction in phase margin, the system is considered to be satisfactory since it's greater than 60 degrees.

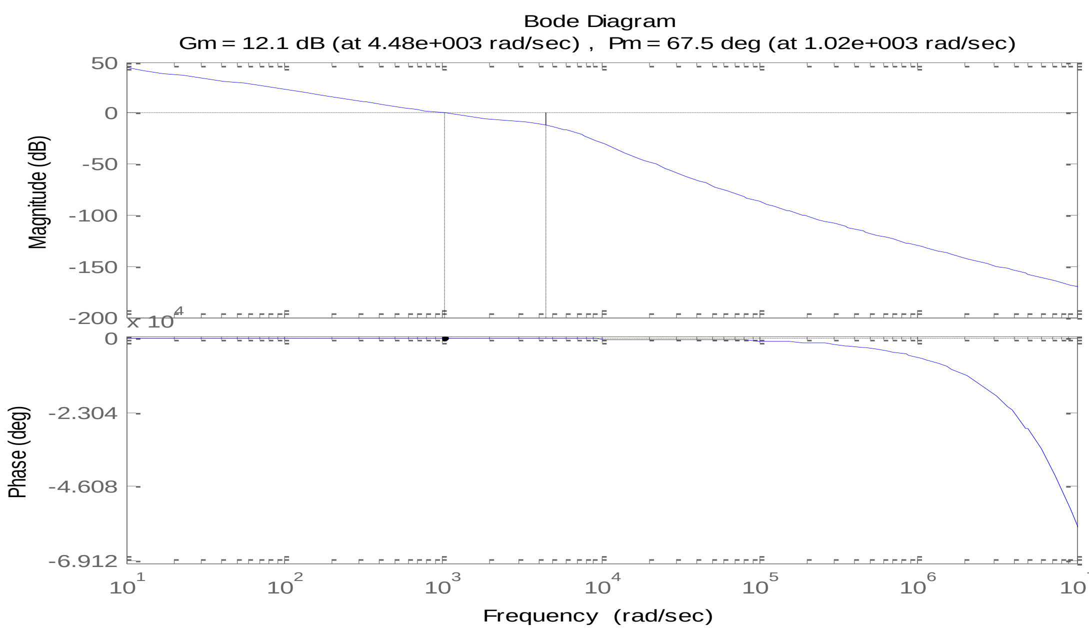


Figure 4.13. Margin Plot for PID Controller after Sampling

The gain of the closed loop system as compared to the specified gain requirement showed that the gain specification has been met for this controller. Table 4.2 and Figure 4.14 show that the system maintains a gain below 0.05 for a range of disturbance frequencies when the system is in closed-loop.

Table 4.2. Disturbance Frequency and System Gain of OBSF

Disturbance Frequency (Hz)	RMS: d(mm)	RMS: x (mm)	lGx,dl = X/ D
8	0.2615	0.01242	0.047495
9	0.4588	0.01510	0.032912
10	0.3385	0.01279	0.037784
11	0.4390	0.01450	0.033030
12	0.4651	0.01874	0.040292

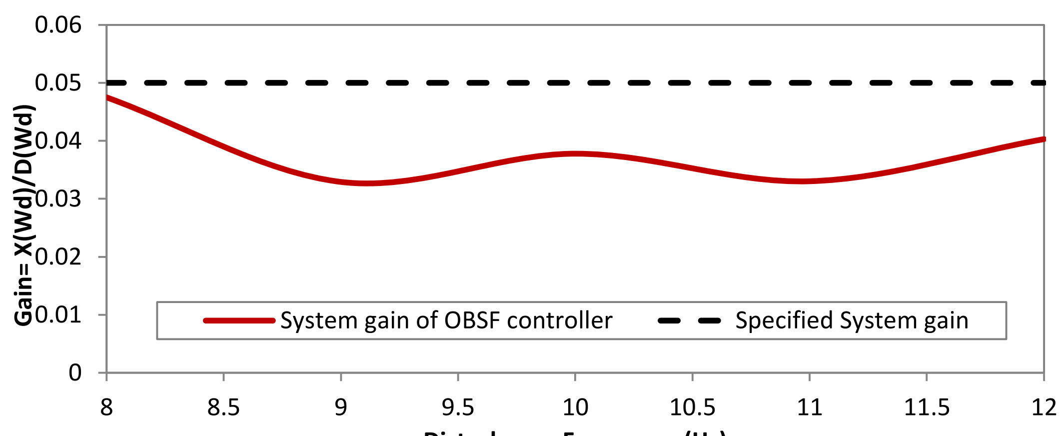


Figure 4.14. System Performance of OBSF Controller

The response of the observer-based state feedback controller when implemented on the real laser beam system is shown in Figure 4.15. Results show that after an input of 12 Hz disturbance frequency, the laser beam movement stabilizes on the position sensing device after switching from open-loop to closed-loop. In open-loop the laser beam vibrates with an amplitude of approximately 0.7 mm, however this vibration minimizes to an amplitude of approximately 0.01 mm at steady-state after switching to closed-loop.

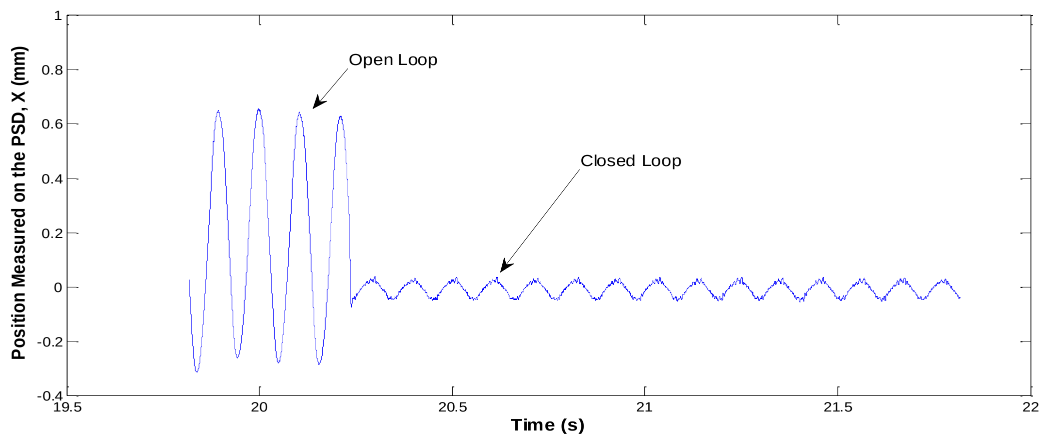


Figure 4.15. Response of Real Laser Beam System with OBSF Controller

After implementing the robust observer on the laser beam system, the gain of the closed loop system is compared to the gain requirements. The system maintains a gain below 0.05 for a range of disturbance frequencies when the system is in closed-loop as shown in Table 4.3 and Figure 4.16.

Table 4.3. Disturbance Frequency and System Gain of Robust Observer

Disturbance Frequency(Hz)	RMS: d(mm)	RMS: x (mm)	lGx,dl = X/ D
8	0.2584	0.007279	0.02817
9	0.3951	0.018680	0.04200
10	0.1878	0.008048	0.04285
11	0.3957	0.019520	0.04011
12	0.3267	0.016560	0.04010

The response of the robust observer when implemented on the real laser beam system is shown in Figure 4.17. Results show that after an input of 12 Hz disturbance frequency, the laser beam movement stabilizes on the position sensing device after switching from open-loop to closed-loop.

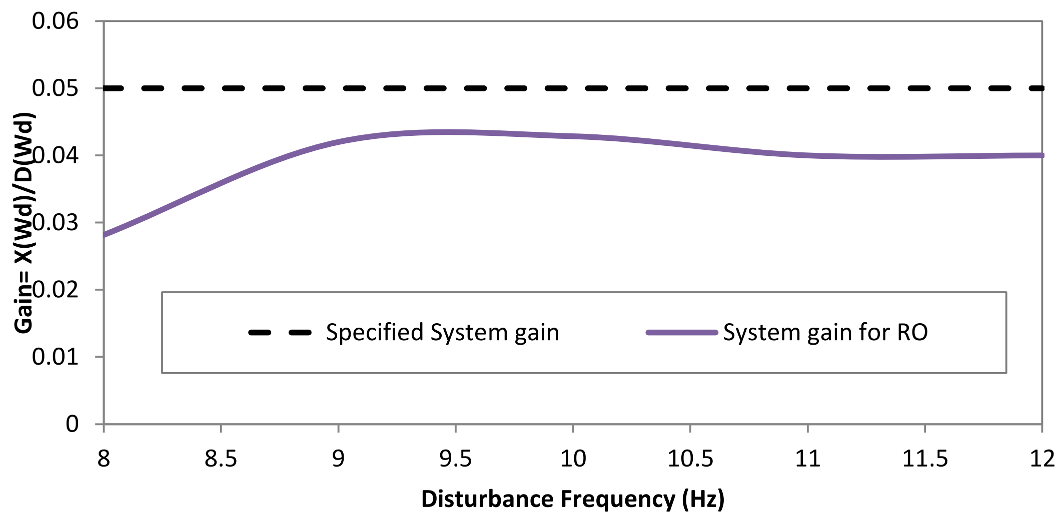


Figure 4.16. System Performance of Robust Observer

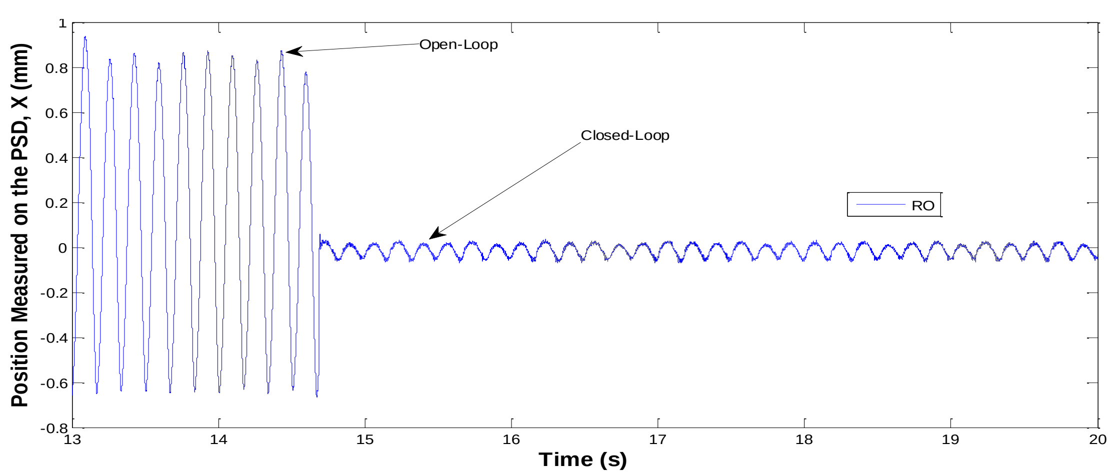


Figure 4.17. Response of Real System with Robust Observer

In open-loop the laser beam vibrates with an amplitude of approximately 0.7 mm, however this vibration minimizes to an amplitude of approximately 0.01 mm at steady-state after switching to closed-loop. The response of the robust observer is similar to the observer-based state feedback controller in Figure 4.15 because the experiment was peformed under very good conditions, and the amount of lighting in the room was regulated.

Comparisons between the controllers are made to investigate the method that best regulates the laser beam, in terms of stabilizing the laser beam. Figure 4.18 is a comparison of the experimental response of the controllers. Figure 4.19 shows a comparison of the controller performance and Table 4.4 describes the differences in the controllers.

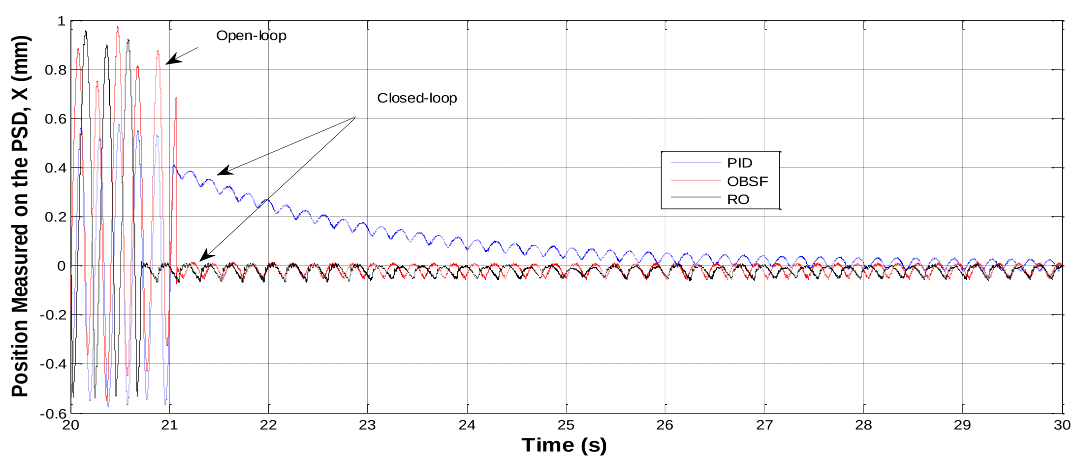


Figure 4.18. Comparison of Experimental Response of Controllers

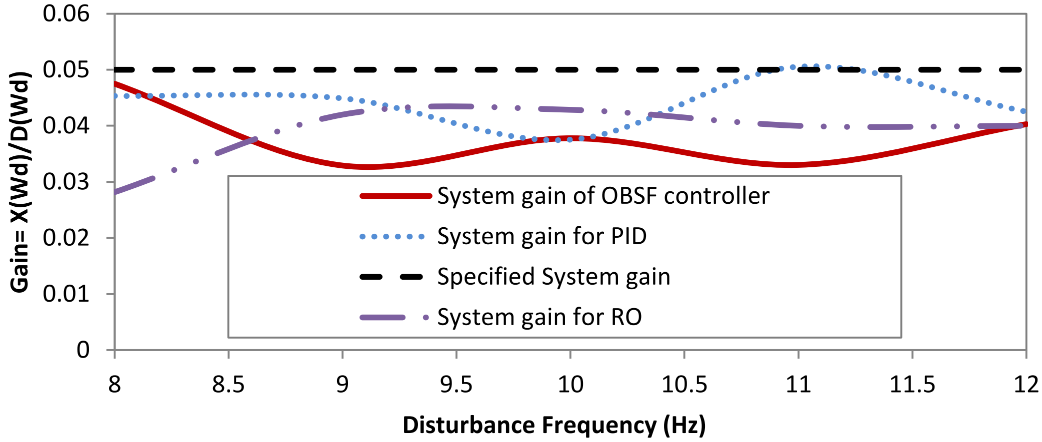


Figure 4.19. Comparison of System Performance for Controllers

Table 4.4. Observed Comparison of Controllers

CHARACTERISTICS	STATE FEEDBACK	PROPORTIONAL INTEGRAL DERIVATIVE
Settling time	Quicker convergence, achieves steady state very fast	Slow convergence, achieves steady state at a slow rate
Accuracy and stability	No filter is required. One does not need to obtain the signal for D action in proportional integral derivative controller	A filter is required when taking the derivative of the signal to be multiplied with k_d.
Design procedure	Compact form. since the model is expressed in matrix-vector form, the calculation is friendly	Design of control requires a relatively complicated process. It handles scalar multi-variable models, and requires designing extra filters for tuning.
Robustness	Handles uncertainty like process disturbance and measurement noise in a simple way	A bit cumbersome in handling noise

After testing all controllers on the real laser beam system, the gains of the closed loop system are compared. The closed-loop gain is observed for a series of different disturbance frequencies. Figure 4.19 shows that in all three controllers, the system maintains a gain below 0.05 for a range of disturbance frequencies.

CHAPTER 5

CONCLUSION

This work presented the design of a proportional integral derivative controller that uses the feedback signal from a position sensing device to rotate the voice-coil actuator. The controller has been designed to stabilize a laser beam such that the incident laser beam on the mirror is reflected to the middle of the position sensor even in the presence of noise and active disturbance. An alternate observer-based state feedback scheme for controlling the laser beam system has been proposed. This controller models the laser beam system as a linear time-invariant plant and estimates the state of the plant by stabilizing the beam at all conditions.

A comparison has been made to investigate the more appropriate and effective control method based on design procedure and performance. Simulation results demonstrate that both controllers are effective and suitable for eliminating vibrations and stabilizing the laser beam on the position sensing device. However, experimental results show that the observer-based state feedback controller is 6 seconds faster, stable because of the absence of filters, and rejects disturbance better by maintaining a lower system gain as compared to the proportional integral derivative controller. The observer-based state feedback controller is relatively simple and the design is straight forward if the model and state of the system can be obtained while the process for the proportional integral derivative controller design is relatively complicated due to the design of filters which alters the stability of the system.

REFERENCES

Arancibia, N. O. P., S. Gibson, et al. (2004). Adaptive control of mems mirrors for beam steering. 2004 ASME International Mechanical Engineering Congress and Exposition, IMECE, November 13, 2004 - November 19, 2004, Anaheim, CA, United states, American Society of Mechanical Engineers.

Arnon, S. and N. S. Kopeika (1997). "Laser satellite communication network-vibration effect and possible solutions." Proceedings of the IEEE 85(10): 1646-1661.

Bodson, M., A. Sacks, et al. (1994). "Harmonic generation in adaptive feedforward cancellation schemes." Automatic Control, IEEE Transactions on 39(9): 1939-1944.

Busack, M., G. Morel, et al. (2010). Breathing motion compensation for robot assisted laser osteotomy. Robotics and Automation (ICRA), 2010 IEEE International Conference on.

Chang, C. S. and T. S. Liu (2007). "LQG Controller for Active Vibration Absorber in Optical Disk Drive." Magnetics, IEEE Transactions on 43(2): 799-801.

Chen, C.-T. (1999). Linear System Theory and Design. New York, Oxford University Press.

Chi-Ying, L., C. Yen-Cheng, et al. (2008). Laser beam tracking by repetitive and variable-order adaptive control. American Control Conference, 2008.

Chua, G.-H., T. Rainsford, et al. (2008). Dynamic laser beam stabilization for terahertz systems. Photonics: Design, Technology, and Packaging III, December 5, 2007 - December 7, 2007, Canberra, Australia, SPIE.

Duarte, F. J. (2009). TUNABLE LASER OPTICS. New York, Elsevier Academic.

Escuti, D. M. (2011). from http://www.ece.ncsu.edu.

Franklin, G. F., J. D. Powell, et al. (1995). Feedback Control of Dynamic Systems. Reading, MA, Addison-Wesley.

Giallorenzi, T. and J. Limb (2009). "Journal of Lightwave Technology publication information." Lightwave Technology, Journal of 27(5): C2-C2.

Glaese, R. M., E. H. Anderson, et al. (2000). Active suppression of acoustically induced jitter for the airborne laser, Orlando, FL, USA, SPIE.

Haddad, W. M. and D. S. Bernstein (1992). "Controller design with regional pole constraints." Automatic Control, IEEE Transactions on 37(1): 54-69.

Hara, K., S. Maeyama, et al. (2008). Navigation path scanning system for mobile robot by laser beam. SICE Annual Conference, 2008.

Horowitz, R., B. Li, et al. (1998). "Wiener-filter-based Minimum Variance Self-tuning Regulation." Automatica 34(5): 531-545.

Jones, A. Z. (2012). "Laser." Retrieved 1/31/2012, from http://physics.about.com/od/physicsitol/g/laser.htm.

Jong-Shik, B., C. Chung Choo, et al. (2006). Anti-shock controller design for optical disk drive systems with a nonlinear controller. American Control Conference, 2006.

Knibbe, T. E. (1993). Spatial tracking using an electro-optic nutator and a single-mode optical fiber. M.S. Thesis, Massachusetts Institute of Technology.

Krokavec, D. and A. Filasová (2007). "Pole assignment in robust state observer design." Robust and Adaptive Control PLUS 2: 75-78.

Kwabena A. Konadu and S. Yi (2011). Design of Controllers for a Laser Beam Stabilizer Using PID and Observer-based State Feedback. 2011 ASME Early Career Technical Conference. Atlanta, Georgia USA.

Landolsi, T., R. Dhaouadi, et al. (2011). "Beam-stabilized optical switch using a voice-coil motor actuator." Journal of the Franklin Institute 348(1): 1-11.

Leigh-Lancaster, C. J., B. Shirinzadeh, et al. (1997). Development of a laser tracking system. Mechatronics and Machine Vision in Practice, 1997. Proceedings., Fourth Annual Conference on.

Li, W., X. G. Chang, et al. (2001). "Design of an enhanced hybrid fuzzy P+ID controller for a mechanical manipulator." Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on 31(6): 938-945.

Luenberger, D. G. (1964). "Observing the State of a Linear System." Military Electronics, IEEE Transactions on 8(2): 74-80.

Mead, R. (2009). "Application of lasers." from http://www.techradar.com.

Ming-Yuan, S. and T. H. S. Li (1995). Implementation of integrated fuzzy logic controller for servomotor system. Fuzzy Systems, 1995. International Joint Conference of the Fourth IEEE International Conference on Fuzzy Systems and The Second

International Fuzzy Engineering Symposium., Proceedings of 1995 IEEE International Conference on.

Ogata, K. (2002). Modern Control Engineering. Upper Saddle River, New Jersey, Prentice Hall Inc.

Perez-Arancibia, N. O., J. S. Gibson, et al. (2009). Laser beam pointing and stabilization by intensity feedback control. 2009 American Control Conference, ACC 2009, June 10, 2009 - June 12, 2009, St. Louis, MO, United states, Institute of Electrical and Electronics Engineers Inc.

Postlethwaite, S. S. a. I. (1996). Multivariable Feedback Control:
Analysis and Design.

Precup, R.-E. and H. Hellendoorn (2011). "A survey on industrial applications of fuzzy control." Computers in Industry 62(3): 213-226.

Quanser (2010). Laser Beam Stabilization Instructor Manual. Quanser Speciality Experiment Series: laser beam system Laboratory Workbook.

Richard T. O'Brien, J. and R. J. Watkins (2011). Adaptive Hinfinity Vibration Control. American Society of Mechanical Engineers Dynamic Systems and Control Conference. Arlington, VA, USA.

Skormin, V. A., M. A. Tascillo, et al. (1997). "Demonstration of a jitter rejection technique for free-space laser communication." Aerospace and Electronic Systems, IEEE Transactions on 33(2): 568-576.

Tsu-Chin, T., S. Gibson, et al. (2011). Adaptive control for focusing of optical drive read/write heads. American Control Conference (ACC), 2011.

Ying, B., Z. Hanqi, et al. (2005). "Fuzzy logic control to suppress noises and coupling effects in a laser tracking system." Control Systems Technology, IEEE Transactions on 13(1): 113-121.

Yokoyama, E., M. Nagasawa, et al. (1994). "A disturbance suppression control system for car-mounted and portable optical disk drives." Consumer Electronics, IEEE Transactions on 40(2): 92-99.

Zhou, K., J. C. Doyle, et al. (1996). Robust and optimal control, Prentice Hall.

Zia, O. (1992). On the control aspect of laser frequency stabilization. Proceedings of the 1992 American Control Conference, June 24, 1992 - June 26, 1992, Chicago, IL, USA, Publ by American Automatic Control Council.

APPENDIX A

MATLAB CODE FOR PID

```
% Load the model parameters, encoder calibrations, and amp saturation.
format long

[ K, tau, K_EC_D, K_EC_C, K_PSD, VMAX_D, VMAX_C ] = setup_lbs_configuration( );

% ************ IDEAL PID DESIGN ************
% **************************************************
% Spec #1: Damping ratio
zeta = 1;
% Spec #2: |X(wd)|/|D(wd)| gain specification (mm/mm)
Ad = 0.05;
% Disturbance frequency: wd = 2*pi*fd (Hz)
fd = 12;
% Spec #3: Zero location.
p0 = 0.5;
% Design the PID controller to meet these specifications
[w0_plot,G_w0,w0,kp,kd,ki] = d_lbs_pid_studentresult(K,tau,zeta,Ad,fd,p0);

% ************ PRACTICAL PID DESIGN ************
% Spec #1: Damping ratio of high-pass filter.
zeta_f = 0.5;
% Spec #2: Natural frequency of high-pass filter (rad/s)
w0 = 563;
wf = 10*w0;
% Frequency that results in the desired disturbance rejection (rad/s)
p0 = 0.5;
K = 2200;
% Corresponding proportional gain (V/mm)
tau = 0.005;
zeta = 1;
fd = 12;
% Disturbance frequency (rad/s)
wd = 2*pi*fd;
% Set Laplace operator to s = j*w
s = sqrt(-1)*wd;
```

```
G_w0 = abs( (tau*s^2+s) ./ (tau*s^2 + 2*zeta*w0*tau*s + w0.^2*tau)
);
ind = find( G_w0 < Ad );
% Frequency that results in the desired disturbance rejection
(rad/s)
w0_des = w0(ind(1)) ;
% Build second-order high pass filter (i.e. derivative with low-pass
filter)
[hpf_tf] = d_hpf(zeta_f,wf);
% Calculate ideal and practical loop transfer functions: L1 and L2
[P,L1,L2] = d_calc_loop_tf(K,tau,kp,kd,hpf_tf);

% ************ FIND REQUIRED SAMPLING TIME ************
% Spec: Desired phase margin (deg).
PM_des = 60;
% Calculate sampling rate needed to achieve desired phase margin.
[fs] = d_lbs_pm_sampling(L2,PM_des);
% Desired sampling time (s)
Ts = 1e-4;
% Add delay from sampling to loop transfer function.
L3 = L2 * tf(1,1,'inputdelay',Ts);
% ************ DISTURBANCE REJECTION  ************
% Spec #1: Center frequency of band-pass filter.
wc = 2*pi*fd;
% Spec #2: Gain of band-pass filter at wd (dB)
A_bpf = 20;
% Build second-order band-pass filter
[bpf_tf,zeta_bpf] = d_bpf(A_bpf,wc);
% Add band-pass filter to loop transfer function.
L4 = bpf_tf * L3;
% ************ OTHER PARAMETERS ************
%[zeta_f_r,wf_r,kp_theta,kd_theta,ki_theta,kp_seek,kd_seek,ki_seek,I
NT_MAX,
%seek          threshold,seek_limit,reset_enc,THETA_INT_DZ]         =
setup_lbs_other_param( );
% ************ DISPLAY RESULTS ************
disp(' ');
disp(' ************************************************ ');
fprintf('PID gains for w0 = %5.2f rad/s and tau = %4.2f s: \n',
w0_des, p0)
fprintf('   kp = %5.3f V/mm \n', kp)
fprintf('   kd = %5.3f V.s/mm \n', kd)
fprintf('   ki = %5.3f V/mm/s \n', ki)
```

APPENDIX B

MATLAB CODE FOR STATE FEEDBACK OBSERVER

```
% Load the model parameters, encoder calibrations, and amp saturation.
% [ K, tau, K_EC_D, K_EC_C, K_PSD, VMAX_D, VMAX_C ] = setup_lbs_configuration( ); format long
%PL=tf([2200],[0.005 1 0]);
[A,B,C,D]=tf2ss([2200],[0.005 1 0])
%size(sys)
%A=[0 1;0 -200];
%B=[0;440000];
%C=[1 0];
%D=[0];
%sys_ss=ss(A,B,C,D)
VMAX_D=100;VMAX_C=100;
ctrb(A,B)
obsv(A,C)
p=[-254.7+441.153i -254.7-441.153i];
K=acker(A,B,p)
t=[-1273.5-2205.8i -1273.5+2205.8i]
%p=[-254.7+441.153i -254.7-441.153i];
L=acker(A',C',t)'
```

APPENDIX C

MATLAB CODE FOR ROBUST OBSERVER

```
A=[-200 0;1 0];
B=[1;0];
C=[0 440000];
D=[0];
n=2;
sys=ss(A,B,C,D);
p=[-254.7+441.153i -254.7-441.153i];
Qn=2;
Nn=0;
Rn=0.0225;
[kest,L,P]=kalman(sys,Qn,Rn,Nn)
obsv(A,C);
%L=lqe(A,eye(n),C,W,V);
eig(A-(L*C))
```