TWO-DIMENSIONAL CCD POSITION SENSOR
SYSTEM FOR ACTIVE MAGNETIC BEARINGS

by

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Abstract

This dissertation reports on an optical-based two-dimensional position sensor for use in Active Magnetic Bearings (AMB) to measure the position of the levitated rotor. The motivation for the deployment of optical technology is the well-known advantage of high precision contactless displacement measurement. The radial and axial edges of the rotor are illuminated by red and green laser beams respectively. The position of the rotor is determined from its image projected on a Charge Coupled Device (CCD) sensor. The measuring principle is demonstrated as a position sampler in the closed loop control of an active magnetic bearing model.

The image representing the position is processed with a real-time algorithm on a Field Programmable Logic Gate Array. The principle of operation of a CCD as a position sensor is analysed in order to establish how the image captured by the CCD can be processed to determine the position of the rotor. A simple AMB is modelled in which the sensor acts as a feedback position device. The main objective of the model is to evaluate the accuracy of the system. The purpose of the overall sensing technique to be used is to achieve highly accurate and precise measurements with CCD-based optical metrology.
Declaration

„I declare that this dissertation is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references and it has not been submitted for any degree or examination at any other university.„

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Signature               Date
P E Sithole
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<tbody>
<tr>
<td>ADC</td>
<td>Analogue to Digital Converter</td>
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<td>AMB</td>
<td>Active Magnetic Bearings</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
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<tr>
<td>CMOS</td>
<td>Complementary Metal–Oxide Semiconductor</td>
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<tr>
<td>CMM</td>
<td>Co-ordinate Measuring Machine</td>
</tr>
<tr>
<td>CNT</td>
<td>Counter</td>
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<tr>
<td>CONVST</td>
<td>Convert start</td>
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<tr>
<td>DPRS</td>
<td>Discrete Response Position Sensor</td>
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<td>DR</td>
<td>Dynamic Range</td>
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<td>DSNU</td>
<td>Dark Signal Non uniformity</td>
</tr>
<tr>
<td>EAB</td>
<td>Embedded Array Block</td>
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<tr>
<td>EOC</td>
<td>End of Convert</td>
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<tr>
<td>FMCLR</td>
<td>Frequency Modulated Coherent Laser Radar</td>
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<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
</tr>
<tr>
<td>HeNe</td>
<td>Helium Neon</td>
</tr>
<tr>
<td>IH-LQG</td>
<td>Infinite Horizon Linear-Quadratic-Gaussian</td>
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<tr>
<td>IL</td>
<td>Image Lag</td>
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<tr>
<td>IPET</td>
<td>Institute of Professional Engineering Technologist</td>
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<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
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<tr>
<td>LPM</td>
<td>Library of Parameterised Modules</td>
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<tr>
<td>PD</td>
<td>Power Down</td>
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<tr>
<td>PID</td>
<td>Proportional Integral Controller</td>
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<tr>
<td>RAM</td>
<td>Random Access memory</td>
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<tr>
<td>ROG</td>
<td>Readout Pulse Gate Input</td>
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<tr>
<td>SE</td>
<td>Saturation Exposure</td>
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<tr>
<td>SMA</td>
<td>Sub-Miniature Version A</td>
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<tr>
<td>TDI</td>
<td>Time Delay Integration</td>
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<tr>
<td>TLA</td>
<td>Tektronix Logic Analyser</td>
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<tr>
<td>TTE</td>
<td>Total Transfer Efficiency</td>
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<tr>
<td>VHDL</td>
<td>Very High Speed Hardware Descriptive Language</td>
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<tr>
<td>VHSICHDL</td>
<td>Very High Speed Integrated Circuit Hardware Description Language</td>
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<tr>
<td>VLSI</td>
<td>Very Large Scale Integration</td>
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Chapter 1

Introduction

1.1 Project overview

The desire to capture an object shape by optical means dates back to the beginning of photography. In the 1860s François Villème invented a process known as photo sculpture, which used 24 cameras to capture a 3-dimensional shape. After a few years, however, as it was realized that the photo sculpture technique still needed significant human intervention, the idea was abandoned. It is only with the advent of digital computers and advancement in optics that the process of capturing shape by optical means has regained substantial interest, more than 100 years later.

In the last twenty years many advances have been made in the field of solid-state electronics, photonics, computer vision and computer graphics, which have allowed the development of compact, reliable and high accuracy 3-dimensional vision systems. In particular advances in Very Large Scale Integration (VLSI) technology and integrated sensor development helped to accelerate the deployment of 3-dimensional vision systems in many fields such as visual communication, industrial automation and cultural heritage preservation.

Developments in 3-dimensional shape capturing by optical technology have also led to the development of optical contactless metrology. Contactless measurement speeds up
automated manufacturing, improves quality and lowers manufacturing costs. Optical instruments are now used to accurately align large parts during assembly, certify tooling and monitor repeatability during production. It can also be used to scan objects that were previously impossible to scan due to their size, inaccessibility, very complex geometry or delicate surfaces. The technology enables an instrument to operate at locations without a conditioned environment and measurements are taken directly from the object surface.

As an introduction to the application of contactless sensors, namely rotating machinery, requirements and applications will be analysed. Precision in rotating machinery most often translates to how precisely the position of the rotor axis can be measured. Active Magnetic Bearings (AMB) is a technology where a rotor is suspended by magnetic forces. The magnetic field strength needs to be continuously adapted by a controller to stabilise the state of the hovering rotor. The efficiency of a magnetic bearing depends on the efficiency of the displacement sensors used.

In order to measure the position of the moving rotor, contactless sensors are used. In the case of AMBs these sensors must be capable of measuring the position of a rotating surface. Consequently, the geometry of the rotor, i.e. its surface quality and the metal properties at the point targeted by the sensor will influence the measurement results. Using Charge Coupled Devices (CCDs) as displacement sensors is an alternative to conventional position sensors.
1.2 Problem statement

The purpose of this study is to investigate and analyse contactless metrological methods using 2D rotor measurements, for position sensing on AMBs.

The principle of operation of a CCD as a position sensor will be analysed in order to evaluate how the image captured by the CCD can be processed to determine the position of the rotor. A simple AMB will be modelled in which the sensor would act as a feedback position device. The main objective of the model will be to establish the effect of the errors caused by the CCD technique. The purpose of the overall sensing technique to be used would be to achieve highly accurate and precise measurements using CCD-based optical metrology. The following is a summary of sub-problems, which were identified and eventually formed the basis of the study.

1.2.1 Contactless metrology study

Different conventional contactless techniques used in AMBs will be reviewed with reference to their principle of measuring a position and their achievable accuracy.
1.2.2 Optical-based techniques comparison

Optical-based position measuring techniques will be reviewed with reference to the principle used to measure the AMB rotor position in order to determine which optical measuring technique best suites AMB applications (See chapter 2).

1.2.3 CCD analysis and implementation

Properties of colour CCDs will be analysed in terms of light sensitivity and frame rate with the objective of using the images of the rotor projected on the colour CCD to measure the position of the rotor by analysing the CCD image pixels (See chapter 3).

1.2.4 AMB modelling

The AMB system model simulations will be analysed with reference to the controller design, feedback, sampled rotor position and rotor velocity estimation in order to verify whether the sensor designed can efficiently and optimally operate in a typical AMB system (See chapters 3 and 4).

1.2.5 Results verification

This last subproblem is to analyse the sensor system measurement results in terms of accuracy in order to find suitable variance values for the system.
1.4 Delimitations

- The hardware setup will be limited to the CCD position sensor design, construction and tests on a stand-alone platform without a physical AMB.
- The active magnetic bearing model will only be limited to the state variable model.
- To verify the sensor implementability on an AMB, a model incorporating sensor parameters will be used for analysis, not a physical AMB setup.
- The sensor measurements and analysis results will be based on a single mechanical hardware experimental setup. Only the software algorithms will be varied.

1.5 Assumptions

- The photo response non-uniformity (PRNU) of the CCD pixels is zero, which implies that the sensitivity of each of the pixels in the line array is uniform when exposed to a uniform illumination.
- Aberrations of the lenses and mirrors that would be part of the sensor system would not have significant error effects on the sensing accuracy.
- The aberration of the laser beam lens is negligible.
- The AMB rotor will not have geometric errors.
1.6 Contribution of the study

The work provides useful information on the development of simple cost effective optical methods of measuring a position of an object. This study would help widen the choice of selecting the type of measuring method for AMB application. It would help in the development of new CCD sensors specifically manufactured for industrial applications as position or displacement sensors. The suggested method in this study is hoped to motivate new innovative ideas on CCD applications e.g. measuring distortion, surface quality and surface profile.

1.7 Research methodology

The method of research employed in this study is experimental in nature and consisted of two phases. The first phase consisted of a comparative study of different measurement techniques and their principles of operation, discussed in detail in chapter 2. The second phase uses the information obtained from the analysis in the first phase to develop and design a prototype for which experimental measurements were conducted.
1.8 Dissertation outline

The dissertation is divided into six chapters. This section gives a brief overview of remainder of this dissertation.

Chapter 2: The literature survey conducted is discussed as a preparatory study that preceded the modelling and design is presented.

Chapter 3: This chapter highlights the system theoretical modelling, mathematical design and controller modelling. The detail system design of the two-dimensional sensor for an active magnetic bearing, the model of a simple magnetic bearing, the controller design and the closed loop simulations of the system is described.

Chapter 4: This chapter gives detailed information on the sensor hardware design, the experimental set-up and its optical components. The software part of the project is also discussed.

Chapter 5: The experimental results, system functional overview and the closed loop system simulations are obtained.

Chapter 6: Conclusion and recommendations of the project are presented for further study.
Chapter 2

Literature Review

2.1 Introduction

This chapter is concerned with the literature review. In the following sub-sections developments and applications of magnetic bearings are briefly discussed. Optical metrology and its applications are also discussed. The last few sections of this chapter discuss the application of contactless sensors to AMBs, including self-sensing AMBs.

2.2 AMB overview

Active magnetic bearings are typical mechatronic products [37]. They are composed of mechanical components and electronic components. These components are sensors, power amplifiers and a controller, which may be in the form of a microprocessor. In addition an increasingly important component is software, which eventually determines the functionality of the system. The improved availability and integratability of these components makes the magnetic bearing a more and more attractive as a solution to classical bearing problems.
Schweitzer [37] reported special advantages of an AMB’s unique properties. These properties allow novel construction, high speeds with the possibility of active vibration control, operation with no mechanical wear, less maintenance and therefore lower cost.

Engineers and scientists are increasingly finding uses of active magnetic bearings in industrial applications. Some of the applications of active magnetic bearings are electric drives, turbomachinery, machine tools, vacuum techniques, textile machinery, energy storage, applications in space and physics, vibration isolation and identification and testing of rotor-dynamics.

2.2.1 The history and the future of AMBs

The idea of letting a body hover without any contact by using magnetic forces is an age old dream. As early as 1842, Earnshow had shown that permanent magnets alone are unable to keep a ferromagnetic body in a free and stable hovering position. A major breakthrough on AMBs was made in 1937 (during the beginning of WW II). Kemper described an experiment in which an electromagnet with a cross section of 30 cm by 15 cm with a magnetic field intensity of 0.25 Tesla and 250W power carried a load of 210 kg over an air gap of 15 mm. For the control, he used inductive sensors, capacitive sensors and valve amplifiers. This experiment was the predecessor of magnetically levitated vehicles. Magnetic levitated (MagLev) transport systems are being researched around the world [6]. The vehicles are magnetically levitated and their guiding and propulsion forces are also generated magnetically. Due to the absence of contact friction, these kind of vehicle easily reach high speeds. MagLev systems have several advantages when compared to traditional
railway systems in that the absence of contact reduces noise, component wear, vibrations, maintenance costs, etc. Maglev vehicles are better able to climb steep ramps, three times greater than conventional steel wheel rail technology can climb and turn on curves with smaller radii. Smaller radii and higher super-elevation coefficients allow construction of shorter guide ways that are more economical [6].

In recent years, many of these magnetically levitated (MagLev) transport systems have been constructed, tested and improved. Vehicle levitation is achieved by controlling the gaps of electromagnets. Bittar [6] devised a technique based on $H_2$ and $H_\infty$ control synthesis for MagLev vehicles using four position sensors. Based on this synthesis, it was demonstrated how system oscillations could be stabilized although different weighting functions had to be employed. Weighting functions were selected to determine the controller closed-loop resonance peak, robustness and sensitivity boundaries. In general weighting functions are selected to analyse relative magnitude of signals, their frequency dependence and their relative importance.

In 1937, Beams and Holmes (quoted by Schweitzer [37]), developed a Maglev apparatus at the University of Virginia. They suspended small steel balls which they brought to very high rotational speeds for testing their material strengths. The rotating balls reached a spectacular speeds of up to 18 million rpm (1885 rad/s) which caused the steel balls to burst under the centrifugal forces experienced.
Engineers are finding AMB applications for wider engineering implementation e.g. aerospace medical apparatus. Several research groups are making good progress on future uses of mechanical circulatory support systems, focusing on implantable applications. Rotary blood pumps are attracting more and more interest from researchers as a next generation of implantable circulatory device. Kim [21] developed an AMB blood pump. The challenge is the size reduction and the complexity of the pump. The proximity sensor wires contribute to the packaging complexity.

The latest development in the field of composite materials and active magnetic bearings have led to kinetic energy storage devices which are small and light and operate at higher rotational speeds. Ahrens [1] reported on modal analysis and vibration behaviour of a magnetically suspended flywheel energy storage device. The axial vibration modes of a flywheel strongly influenced the radial vibration behaviour of the rotor. Modal analysis identified these modes and provided important information on the vibration behaviour of the rotor.

In conclusion, according to Schweitzer [37], AMBs are currently expensive due to their complexity. According to Noh [31], the position sensors and the control law applied determines the cost and reliability respectively. Some aspects such as safety, reliability and optimal design variations are still in question. New technologies are readily becoming available to solve these problems.
2.3 Contactless metrology and applications

The aerospace and automotive industries have taken the lead in finding innovative solutions to measurement problems [47]. A wide range of automotive components utilizes contactless metrology during its production. Contactless sensors enhance manufacturing, improves quality and lowers manufacturing costs. It can be used to certify tooling and then monitor repeatability during production. In addition, it can also be used to scan objects that were previously impossible to scan due to their size, inaccessibility, very complex geometry or delicate surfaces.

2.3.1 Optical techniques

Gonzo [14] reported on the currently known optical techniques that can be used to register three-dimensional images (See figure 2-1). Depending on the measured range, and on the required accuracy, some techniques have advantages with respect to others. The distinction between active and passive techniques is due to the use or absence of light sources aiding the detection process. Displacement sensor based on the position from shading technique (See figure 2-1 under passive methods) will be discussed later in this chapter.
2.4 Lasers application in optical metrology

2.4.1 Diode lasers

Diode lasers are becoming an important tool for dimensional, alignment and proximity metrology. Stone [43] implemented diode lasers for absolute interferometry and tried to identify other length-measurement applications that can exploit the unique characteristics of diode lasers. In many aspects a diode laser is not as well suited for length measurement as the ubiquitous helium-neon (He-Ne) lasers, because the He-Ne laser has better beam quality, better wavelength stability and better coherence. However, in some applications the characteristics of diodes can be crucial to the success of a measurement and allow the development of new techniques that are not possible using a He-Ne laser.
The diode lasers used in laser pointers are small, inexpensive devices which can be powered efficiently from a battery. These are useful attributes, but perhaps more important for optical metrology are the unique spectral characteristics of these laser diodes. Some metrology applications benefit from using a colour other than red or green beam e.g. a 1.5 µm diode is well suited for measurement of silicon wafer thickness. This is because silicon is transparent at this wavelength. However, in this study red and green lasers will be used.

2.4.2 Frequency Modulated Coherent Laser Radar (FMCLR)

Most existing contactless systems require sensors that measure only in close proximity to the surface of interest. White [47] reported on a new generation of FMCLR instruments that precisely measures large-scale geometry without requiring photogrammetry dots, laser tracker spherically mounted retroreflectors, retroreflectors or probes. Although the technology has been used by U.S. government agencies since 1993, it has only recently become available in a commercial system that can be integrated more easily into remote automated manufacturing systems [47].

2.4.3 Basic concept of FMCLR and applications

The newest commercial instruments utilizing FMCLR are Leica LR200 and MetricVision's MV200, which takes a fresh approach to industrial design. The MetricVision system operates using a sensor to direct a focused invisible infrared laser beam to a point and coherently processes the reflected light. As the laser light travels to and from the target, it
also travels through a reference path of calibrated optical fiber in an environmentally controlled module. The two paths are combined to determine the absolute range to the point. The distance measurement is then combined with the positions of the two precision encoders to determine a point on a surface in space. An invisible spot is focused on a part surface and two visible red laser beam support measurements. The first is a large-dot pointing laser. It gives an easy-to-see (but approximate) location of the invisible measuring beam. A second, red, laser beam is precisely coaxial to the measurement beam, which is smaller compared to the first and gives a very accurate location of the invisible beam's position.

Red light utilized emanates from a fiber-pigtailed 660 nm red laser. The red dot is as small as the finely focused infrared light. A fiber-optic coupler injects the red-laser light into the fiber that propagates the infrared light. Special optical coatings are used on the internal mirror, focusing lenses and exit window to allow dual wavelength operation. This solution minimizes light loss without sacrificing sensitivity. FMCLR are best suited for long-range measurements. Their resolution is only limited to about few microns. Therefore, they will not be suitable for position measurement on active magnetic bearings because one of the features of AMBs is that the rotor is in close proximity to the electromagnet.

Miyagawa [25] implemented a time-of-flight method in which the distance of an object was estimated by measuring the delay of the received light pulses relative to the transmitted light pulse. The delay time was measured as a phase shift by two sensing periods. The sensor detected the difference of 10 cm at the range of 50 cm in the dark background. The light detector they used was a special fabricated CCD (Charge Couple Device). Although
the principle was successful there was some ambiguity interval at ranges that were multiples of $ct_w$ where $c$ was the speed of light and $t_w$, the pulse duration.

### 2.5 CCDs applications in metrology

When a specific type of light is used in metrology, a compatible detector must be used. In this study, there are two capable sensors usable, CCDs and CMOS (Complementary Metal–Oxide Semiconductor) sensors. To briefly introduce the advantages of CCDs in metrology, Axis [3] recommended using a CCD-based sensor in all situations where image quality or light sensitivity is of the highest concern. For applications where cost or size is critical, a CMOS-based sensor is most likely the best solution. The motivation for this statement is that CCD sensors have high light sensitivity, better colour sensing ability and sharper images and low background noise while CMOS sensors has low light sensitivity and higher noise ratio. Some drawbacks of using CCD sensors are they are more expensive to produce and more complex to incorporate while CMOS sensors are less expensive and easier to design. Although CCD sensors are more expensive than CMOS sensors in general, linear CCDs are less expensive.

More researchers are implementing CCDs in applications ranging from profiling characterisation to proximity detection. Researchers are struggling to find the relevant sensors for their applications [35]. Some advanced institutions have succeeded in manufacturing their own CCDs for their CCD-Based Range Finder Project [25]. The major drawback of CCDs is their data rate. The higher the clock frequency, the lower the sensitivity ([2], [42]). This is very important for the position sampling rate, which is related to the frame rate (to be discussed in
chapter 3). The trade-off between the CCD clock speed and the sensitivity is getting better as time progresses.

### 2.5.1 Some shadow methods implemented with CCDs

Shadow methods are the methods of interest in this study. The approach illustrates a method proposed by Fischer [12]. The shadow methods of position measurement use a shadow, projected by a measured object, onto a CCD sensor without a lens to determine the measured object’s edge position [33]. Both linear and array CCD sensors are applicable for these measurements. The position of an object is determined from the position of the projected shadow (see figure 2-2). Therefore the range of measurable positions is limited by the CCD sensor’s length. The positions are considered with respect to some reference point, usually to the first pixel of the CCD sensor. The relation between the measured object’s edge position and the position of the edge in the illumination profile (shadow position) on the CCD sensor depends on the characteristics of the light source. The image formation is demonstrated using a white light source and parallel beam in figure 2-2 and figure 2-3 respectively.

![Figure 2-2: Principle of shadow methods [12]](image-url)
2.5.1.1 Position measurement using a source of parallel beams

Fischer [12] constructed the setup in figure 2-3 which consisted of a light source of parallel beams that used a lens and a point light source placed in focus of the lens.

![Figure 2-3: Edge position measurement using parallel beams [12]](image)

The illumination of the CCD sensor using this light source was not uniform. This was caused by effects such as diffraction of light on the lens’s shutter, reflections in the laser diode’s housing and non-homogeneous radiation across laser diode chip’s area. This non-uniformity affected accuracy of position determination. The prototype constructed to verify the above method consisted of a laser diode and a double convex lens with a focal length of 50 mm, linear CCD sensor Sony ILX703A and a sensor control and signal-processing unit. With this device several measurements such as linearity measurement were performed. The linearity error \( \Delta \) was in the range of ± 30 \( \mu \text{m} \). Position resolution was 0.8 \( \mu \text{m} \). Linear interpolation was used to increase the resolution.
2.5.1.2 Position measurement using a point light source

Fischer [12] also used a point light source to illuminate the measured object; the object’s edge position was different from the position of the edge in the illumination profile on the CCD sensor (see figure 2-4). This was caused by the divergence of the light beams emitted from the point light source.

![Diagram of position measurement using a point light source](image)

**Figure 2-4: Position measurement using point light source [12].**

The true position of the object’s edge \( x_E \) was determined from the light source’s position \( L \), from the position of the edge in the illumination profile \( x_M \) and from distances measured object CCD sensor \( y_1 \) and light source CCD sensor \( y_2 \). Equation (2.1) gives the position of the object.

\[
x_E = \frac{y_1}{y_2} (L - x_M) + x_M
\]  

(2.1)
2.5.2 Overview of variable angle triangulation method

The variable angle method uses a triangulation measurement principle as follows (See figure 2-5). A laser beam is reflected off the target surface and passes through an optical centre shown in figure 2-7. The beam is focused on a CCD sensing array. The CCD detects the peak value of the light quantity distribution of the beam spot for each pixel. Beraldin [5] and Gonzo ([15], [14]) implemented this method, but not for displacement measurements. In their case they wanted to capture a 3-D shape of an object using a CMOS sensor as a laser detector.

Knowing two angles (\( \alpha \) and \( \beta \)) of a triangle relative to its base (baseline \( D \)) determines the dimensions of the triangle formed by the laser beam. By trigonometry, the \((X, Z)\) coordinates of the illuminated point on the object is

\[
Z = \frac{D f}{p + f \tan(\alpha)}, \quad \text{and} \quad (2.2)
\]

\[
X = Z \tan(\alpha) \quad \text{(2.3)}
\]
where $p$ is the position of imaged spot on the CCD, $\alpha$ is the deflection angle of the laser, $f$ is the effective distance between the position sensor and the lens.

Another closely related method was implemented by Early [11] for relative alignment monitoring. Early implemented a 2048 linear pixels CCD as a laser detector. The resolution obtained was about 2 - 10 µm but it decreased to about 10 - 25 µm after a few days in operation. This was caused by laser beam motion-pointing corrections and thermal effects.

2.6 AMB precision position control

2.6.1 Nano-metre motion control overview

Recently, many reports have been concerned with development of nano-metre motion control [1]. The pattern width of LSI (Large Scale Integrated) semiconductors (1G DRAM) is becoming less than 0.2 µm with an overlay tolerance of less than 60 nm, which is still to be achieved in a few years to come.

To realize an accuracy of such high degree, the following are some of the key determining factors: Machine mechanism elements such as bearings and guide ways, mechanisms such as positioning tables and actuators to drive mechanisms such as piezoelectric actuators. To generate ultra-precision motion, basic machine elements such as bearings and linear guide ways must be sufficiently accurate. However, it is impossible to manufacture parts of the bearings and guide ways without any geometrical profile error. This means there exist no machine elements free from motion error.
The current development in the field of optical sensors is primarily directed towards lower cost compact sensors that measure several diameters simultaneously.

Molenaar [27] designed a Suspension and Propulsion Unit (SPU). The challenge was to build a magnetic suspension and propulsion system with a long stroke (up to several tens of millimetres) and with sub-micrometre accuracy both in suspension and propulsion direction. A good example of a sub-micrometre accuracy positioning system can be found in an IC-lithography wafer stepper. In a wafer stepper two perpendicular motions (X-Y motion) must be achieved within a plane.

Molenaar’s [27] experimental set-up used three types of sensors: Eddy current sensor for the suspension and both capacitive and Heidenhain incremental optical encoder for the X, Y and rotational angle directions. The measurement experiments were concerned with position accuracy, bandwidth and stiffness. Their results clearly pointed out that sensor noise caused by magnetic interferences were the main drawback to achieving higher accuracy and bandwidth. Crosstalk between the X and the rotational angle caused vibration due to the eddy current excitation clock frequency.

2.6.2 AMB Position Sensors

There are several types of position sensors that have been used or have potential to be used in magnetic bearing applications ([24], [7], [31]), such as ultrasonic probes, hall effect probes, capacitance probes, laser probes, variable reluctance probes, eddy current probes and optical probes.
From Schweitzer [37], Noh [31], Boehm [7] and the other experts on AMBs, the requirements of these position sensors for magnetic bearing applications were that operation must be contactless, bandwidth of the sensor should exceed that of the amplifier and the bearing and sensors need to be durable, stable and affordable.

### 2.6.2.1 Ultrasonic probes

Ultrasonic probes measure the acoustic impedance which depends on the targeted object’s position. This sensor type has the advantage of a very long range (ideal for measuring coal storage, grains in a silo etc.) and usually has good dynamic (bandwidth) and static (linearity) characteristics ([7], [31]). A major drawback of this type of sensor is that the resolution is too low to be used in magnetic bearing applications [31].

### 2.6.2.2 Hall effect probes

When a magnetic field penetrates a semiconductor plate perpendicular to the current, the Lorentz force produces a potential difference across the plate. The potential difference, called the Hall voltage, is proportional to the product of the current across the Hall element and the magnetic field strength. The Hall effect sensors can be made very small in size at low cost. Compared to other types of sensors, however, even the temperature compensated Hall effect sensors have high sensitivity to temperature changes. Moreover, the output of the sensor is highly susceptible to magnetic noise ([31], [7]). Another disadvantage is that they have a slow response [31].
2.6.2.3 Capacitance probes

Capacitance position sensors work on the principle of an ideal plate capacitor whose reactance changes linearly with distance between the two capacitor plates, one of which can be the levitated body in AMB applications [10]. This type of sensor usually has good stability and linearity characteristics. Figure 2-6, shows the output signal at different excitation frequencies [31].

![Figure 2-6: Response voltage of a capacitance displacement sensor close to its resonance frequency 30.4 kHz using spacing variation [31].](image)

Furthermore, capacitance transducers are not affected by magnetic fields and have low temperature drift. The main disadvantage of capacitance type sensors is that they have very poor dynamic characteristics ([7], [31]). Schweitzer [36] suggested an additional software algorithm to solve this problem.
2.6.2.4 Optical probes

Optical sensors are widely used in many industrial applications including magnetic suspension systems [9]. This type of sensor comes in several variations, but usually consist of a light emitting diode and a photosensitive element. The principle of operation could be based on interferometry, reflectance of the targeted material or occlusion. Generally, optical sensors have high bandwidth and excellent linearity. One of the drawbacks of optical sensors is that the transmittance of the space between emitter and receiver must remain constant - a condition which precludes these sensors from many applications [7].

2.6.2.5 Laser probes

Another optical sensor is the laser displacement sensor based on the triangulation of a light beam ([15], [14], [5]). A laser beam is emitted from a laser diode and the levitated object reflects the beam diffusely. A linear position sensor element is focused onto this point and depending on the location the reflected light hits this element of the sensor a distance-dependent signal is obtained. This sensor type is sensitive to the reflectivity of the levitated object. Surface changes of the object influence its accuracy. The cost of laser sensors is relatively high compared to other types of optical sensors. Laser sensors may not be used in canned pump applications unless the canning material is transparent [31].
2.6.2.6 Variable reluctance probes

A variable reluctance probe relies on the principle that the reluctance of the air gap between the probe and the target is linear to the distance between them. The probe senses the impedance change of the carrier signal due to reluctance variation. The frequency of the carrier should be lower than that of the eddy current sensor. The bandwidth of the sensor is limited by the eddy current effects but can be realized up to 2 kHz. The cost of this sensor type is much lower than that of eddy current probes.

2.6.2.7 Eddy current probes

Eddy current position sensors are the most commonly used sensors in magnetic bearing systems ([7], [31]). This sensor consists of a probe tip which contains either one or two coils. The currents in these two coils oscillate at a high constant frequency typically between 0.5 - 2 MHz. Their principle is based on inductance change, generated in the coils in proportion to the metal target proximity. The coil then converts the inductance to a position signal through a balance circuit.

Montie [28] used the Bently-Nevada [4] eddy current probes with a range of 8 V/mm in his experimental test-rig. With the motion within a range of ± 75 µm to reduce the chances of saturating the bearings. The typical output range of the probes was thus ±0.5 V with a constant-magnitude noise of 0.06 V. This was a significant amount of noise, especially for very small motions around the equilibrium centre. This made determining gain and phase at high frequencies very difficult.
The eddy current probes had a significant problem with cross-talk between adjacent probes (orthogonal probes for a single bearing). This cross talk was caused by using different oscillator crystals for each probe and resulted in a high-frequency oscillation superimposed on the position output. The main drawback of eddy current probes is the cost of the sensors [31]. They constitute a significant part of the overall cost of a magnetic bearing system.

2.6.3 Self sensing magnetic bearings

Self-sensing magnetic bearings have been investigated by various researchers in the past ten years. Their efforts can be grouped into two broad categories which differentiate the underlying theoretical approach. One category is parameter estimation where the bearing air gap is treated as a time-varying parameter of an isolated dynamic magnetic system, the bearing and amplifier combination. The other approach is to treat the magnetic bearings and the supported object as a whole. In this case, the position of the supported object is a state rather than a parameter.

2.6.3.1 State-space observer

Vischer ([46], [26]) used a linear state-space observer to estimate the gap displacement. The magnetic bearings are treated as a two-port system input and output. The linearized state-space equation describing the system was observable as well as controllable with the voltage as input and the current as output. Past work on the state-estimation (observer) technique yielded systems which were stable, but only marginally so. These systems
suffered from low robustness to changes in controller parameters and low position stiffness ([36], [22], [45], [30], [28]). Some relatively recent work [45] has focused on the design of controllers and applications of this linear observer based approach to self-sensing and they yielded the same results as past work.

2.6.3.2 Parameter estimation

Okada [32] reported a realisation of a self-sensing magnetic bearing using a demodulation technique. Since the gap displacement modulates the amplitude of the switching waveform, the switching frequency component of the voltage and the current is a direct indication of displacement. Kucera [22] developed the approach which relied on the effects of the driving (voltage and current signals) switching amplifier to estimate position [22].

Other work ([28]) has focused on the use of hysteresis amplifiers to estimate the rotor position from the switching frequency. However, this method suffers from unacceptably low bandwidth due to the time delay of performing the frequency-to-voltage conversion.

2.7 Conclusion

Developments and applications of active magnetic bearings have been discussed and that there have been interests to exploit the AMB’s advantages. Active magnetic bearings were successfully developed but the main concern is their robustness, which is directly linked to their position sensors. One of the most developing fields of technology is nano-metre motion control. It is concerned with control algorithms but also mechanisms, measurements
and actuators. The challenging task in precision engineering is positioning and nano-metre motion control. The trend of almost all researchers is to eliminate all the position sensors making it self-sensing. Although there have been some successes on self-sensing, the controller parameters of the self-sensing magnetic bearings still needed to be tuned at different position levels of the rotor. In addition, magnetic bearings are highly non-linear and various uncertainties such as errors of the parameters, idealised parameters and un-modelled dynamics make self-sensing questionable.

The discussed developments on optics such as lasers and photon sensors such as CCDs gave an incentive to take advantage of this technology to develop a two-dimensional sensor for active magnetic bearings, using a colour CCD and two colour lasers. Fischer [33] proved (resolution and linearity) the capability of this simple optical method. The combination of colour diode lasers and colour CCDs is an unexplored method, which is capable of multi-dimensional measurements. Moreover, this optical measuring method is more linear than most sensors and the signal is directly digitized from the CCD sensor.
Chapter 3

Theoretical Considerations

3.1 Introduction

This chapter presents the theoretical background and modeling aspects of this project. The principle of the CCD position sensing method is presented. The measurement method using a colour CCD is described including the achievable resolution. The formulated and simulated AMB model, including the design of a state feedback controller is presented. Practical aspects pertaining the measurement process are discussed.

3.2 Measurement principle

The position of a rotor is measured by detecting the percentage of the laser beam it obscures from the sensor. The edges of the rotor are illuminated by a narrow red and green laser beam (See figure 3-1). Along the line of sight the beam is deflected by mirrors to a diverging lens. These beams are then spread by the diverging lenses, which then focuses the expanded beams on the CCD. The radial and axial movement of the rotor will change the width of the green and red laser beams respectively. The lens expands the laser beam directed onto the CCD sensor.
3.3 Resolution of the sensor

The dynamic range of the illustrated method, depends on the light spread (magnification) factor of the lens and the CCD pixel size and number of pixels. For the calculation of the resolution the following method was used. The colour CCD (ILX533k from SONY®) used in these experiments, has 2700 active pixels, each pixel has the dimensions $8\mu m \times 8\mu m (8\mu m \text{ pitch})$. The length of the CCD’s active region is calculated as the width of each pixel, multiplied by the total number of active pixels. The active region is therefore calculated to be $P_L = 8\mu m \times 2700 = 21.6\text{mm}$, excluding the dummy pixels at
either end of the array. Thus \( P_L \) is the length of the group of pixels, which effectively detects the beam representing the measured position.

The specification range of the rotor freedom considered is \( 100 \mu m \). Since each pixel the data can be read, distinguished and quantified, and the resolution can then be calculated. Representing the range of \( 100 \mu m \) by 2700 pixels, implies that the resolution is

\[
R_e = \frac{R_a}{N_p},
\]

(3.1)

where \( R_a \) is the range, \( N_p \) the number of active pixels. The resolution, \( (R_e) \), is calculated to be 37 nm.

### 3.4 Laser beam expansion

To achieve the calculated resolution, the range is translated to the optimum range of effective pixels length (\( P_L \)). This is possible, using the following laser beam expansion method. The laser beam must pass through the \( 100 \mu m \) gap and be projected onto the CCD, after being expanded. Having the range \( (R_a) \) and length of the CCD, active region (\( P_L \)), the expansion ratio is calculated to be

\[
m = \frac{P_L}{R_a} = \frac{21.6}{0.1} = 216.
\]

(3.2)
Note that the expansion ratio is only applicable if the focal length of the lens is perpendicularly aligned to the centre of $P_L$. Finding a lens, which can magnify a 0.1 mm beam to 21.6 mm within a range of one metre, needs special manufacturing and is expensive. To avoid this cost and accommodate readily available lenses, it can be shown that $m$ can be changed by tilting the CCD or the beam trajectory. The focal length of the lens with such magnification can be determined (See figure 3-2) by knowing $d$, the distance between the lens and the CCD, the measured range $m_r = 2R_o$ and the CCD active region length $P_L = 2R_i$. The following equation,

$$f = d \frac{R_o}{R_i},$$  \hspace{1cm} (3.3)

therefore holds. Having a lens with a focal length $f$ (See figure 3-2) and requiring the distance $d$, from equation (3.3) results in

$$d = f \frac{R_i}{R_o} = f \times m.$$ \hspace{1cm} (3.4)

![Figure 3-2: Laser beam expansion.](image-url)
3.5 CCD operational principle

3.5.1 CCD sensitivity

The incident exposure represents the total amount of incident photons on the sensor. It is described by the product of the illumination on the sensor surface and the exposure time. The sensitivity of linear CCD sensors depends a great deal on the spectrum of the light source (See figure 3-3). The illumination is the sum of the light energy per unit area. However, a coefficient adjustment is done for luminous efficiency to incident light.

![Figure 3-3: CCD spectral characteristics sensitivity [42].](image)

The colour CCD consists of three line arrays, each sensitive to light of a specific wavelength. Figure 3-3, curve (a) has a maximum sensitivity at 455 nm, curve (b) at 535 nm and curve (c) at 620 nm. This represents the wavelength of blue, green and red light respectively.
The sensitivity is the ratio of the output voltage to the incident exposure \((v/l_x s)\). Here \(v\) is the voltage, \(l_x\) is the illumination (amount of incident photon per unit time) and \(s\) is the exposure time in seconds. The incident exposure is \(l_x s\), the product of illumination on a sensor surface and the exposure time. The value of illumination is considered the amount of incident photons per unit time. Illumination is calculated as

\[
l_x = \int E(\lambda) \times L(\lambda) \ d\lambda, \tag{3.5}
\]

where \(E(\lambda)\) is the luminous energy at specific wavelength and \(L(\lambda)\) is the luminous efficiency coefficient at a specific wavelength.

### 3.5.2 CCD data readout

A CCD is configured as a DPRS (Discrete Response Position Sensor) embedded with shift registers for sequential reading (See figure 3-4). All the photo detectors have to be read sequentially before determining the position. Although in practical applications precision is important, accuracy is even more important. Accuracy is the true value of the quantity. CCDs are very accurate since when combined with appropriate signal processing algorithms, it becomes possible to eliminate false signals generated by a cluttered environment from those signals that truly represent a selected point on the target surface.
The SONY® ILX CCD series devices are reduction-type linear sensors ideally suited for such applications as copiers, facsimiles machines, image scanners and bar code readers. The linear sensors employ the unique HAD (hole-accumulation-diode) sensor technology and therefore exhibit ultra-low image lag compared to non-linear CCDs, good linearity in low illumination conditions and low dark signal output.

Figure 3-4: CCD registers architecture and controls [42].

To obtain the CCD output signal, clock pulses for transfer ($\phi_1$ and $\phi_2$) and a reset pulse ($\phi_{RS}$) are required (See figure 3-5). The data rate is the same as the frequency ($f_{\phi_{RS}}$) of the $\phi_{RS}$ pulse. The $\phi_{ROG}$ controls the end and beginning of the cycle.
The CCD has 3 linear arrays, with separate registers. The frequency in which the charge is transferred is synchronized, but they have different intervals of ROG (Read Out Gate) i.e. $\phi_{ROG-R}$, $\phi_{ROG-G}$ and $\phi_{ROG-B}$ for Red, Green and Blue light respectively.

![Figure 3-5: CCD register sample shifting.](image)

The linear CCD is controlled in TDI (Time Delay Integration) mode. In this mode a value of each output pixel is determined from values of all active pixels at corresponding times. The maximum sampling rate and the frame rate of the sensor are calculated using the CCD maximum clock frequency. The following relationship

$$F_r = \frac{F_\phi}{N_{clk}},$$

holds where $F_\phi$ (3MHz) is the CCD Clock frequency and $N_{clk}$ (2770) the number of clocks required, corresponding to the total number of pixels including the dummy pixels.

The frame rate $F_r$ was calculated to be 1.08 kHz, which translates to a frame period of 0.93 ms.
3.6 AMB model and design

When a voltage is applied to a coil it produces a current. The current sets up a magnetic field, which produces a magnetic flux. The magnetic flux (See figure 3-6) produces a magnetic force given by

\[ f = B^2 A_p / \mu, \quad (3.7) \]

\[ B = \phi / A_p, \quad (3.8) \]

where \( \phi \) is the flux, \( B \) is flux density and \( A_p \) is the area of one pole. The flux is defined by

\[ \phi = Ni / (\ell / \mu A), \quad (3.9) \]

where \( Ni = \) magneto-motive force \((mmf)\), \( \ell / \mu A = \) reluctance, \( A = 2A_p \) and \( \mu = \) permeability depending on the material of the flux path. The mechanical force exerted by a single magnet is

\[ f_0 = 2 \frac{1}{2} \phi^2 / (\mu A_p) \]

\[ = \frac{1}{4} (N^2 \mu A_p) i_0^2 / x_0^2, \quad (3.10) \]

where \( x_0^2 \) is the equilibrium size of the air gap under steady state operating condition. For the current control model the force depends on two variables the current, \( i_0 \) and the air gap, \( x_0 \). The primary goal of the control is to stabilize the rotor at the selected equilibrium position. This equilibrium is defined as the position where the sum of all the forces acting on the rotor becomes
zero. A proper control system should not allow $x_0$ changing much or for long before equilibrium is restored.

![Figure 3-6: AMB single magnet model.](image)

The coil voltage is

$$v = Ri + L_x \frac{di}{dt} + K \frac{d}{dt} \left( \frac{i}{x} \right),$$

(3.11)

where $L_x$ is the operating point constant inductance, $K = \frac{N^2 A \mu}{2}$ and $R$ is the windings resistance. In this case, there are two forces, the gravity force $mg$ and the opposing magnetic force $f_m$. The vector sum of the forces is $f = f_m - mg$. Next $f$ will be analysed to find the characteristic of the current that controls it. Note that $mg$ is constant i.e. only $f_m$ varies depending on the position of the rotor. The total instantaneous force $f$, which is a function of displacement and current, is given by a single equation, linearized around the equilibrium point, i.e,
\[ f = k_i i + k_x x, \quad (3.12) \]

where

\[ k_i = 2 f_0 / i_0 = (2 / i_0) \frac{1}{4} (N^2 \mu_A) i_0^2 / x_0^2, \quad (3.13) \]

\[ k_x = 2 f_0 / x_0 = (2 / x_0) \frac{1}{4} (N^2 \mu_A) i_0^2 / x_0^2. \quad (3.14) \]

In addition \( k_i i \) is the force as a result of the current \( i \) and \( k_x x \) is the additional force due change in the size of the air gap. Analysing the closed loop equation, the force \( f \) is the input and the position \( x \) is the output. For any disturbance of the rotor from the equilibrium point the force \( f \) has to accelerate the mass with force \( m\ddot{x} \). Thus \( f \) is described by

\[ f = m\ddot{x}, \text{ where } m \text{ is the mass and } \ddot{x} \text{ is the acceleration.} \quad (3.15) \]

Substituting equation (3.11) in equation (3.14) result in

\[ m\ddot{x} = k_i i + k_x x. \quad (3.16) \]

Taking the Laplace transform of equation (3.15), assuming the initial conditions to be \( \dot{x}(0) = 0 \) and \( \ddot{x}(0) = 0 \) the following position-current transfer function is obtained

\[ G(s) = \frac{X(s)}{I(s)} = \frac{k_i}{s^2 + \frac{k_i}{m_i}} \quad (3.17) \]
The state vector $\mathbf{x}$ for one-degree of freedom system as in figure 3-6 is composed of two variables position $x$ and velocity $v$ (velocity ($\dot{x}$) is the integral of displacement ($x$) and acceleration ($\ddot{x}$) is the integral of velocity):

$$\mathbf{x} = \begin{bmatrix} x \\ \dot{x} \end{bmatrix}, \quad \text{where} \quad \dot{x} = v. \quad (3.18)$$

By application of Mason’s gain formula about signal flow by observation a state equation is derived from equations 3.17 and 3.18 giving the state equation,

$$\dot{\mathbf{x}} = \mathbf{A}_c \mathbf{x} + \mathbf{B}_c u, \quad \text{where} \quad \mathbf{A}_c = \begin{bmatrix} 0 & 1 \\ \frac{k_x}{m} & 0 \end{bmatrix} \quad \text{and} \quad \mathbf{B}_c = \begin{bmatrix} 0 \\ \frac{k_i}{m} \end{bmatrix}. \quad (3.19)$$

As described by Schweitzer [37] a model that more precisely account for the stored energy in the magnetic field of the bearing then equation (3.19) (by taking into consideration the dynamic behaviour of the inductive electrical circuit) is given by

$$\begin{bmatrix} \dot{x} \\ \dot{\dot{x}} \\ \dot{i} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{k_x}{m} & 0 & \frac{k_i}{m} \\ 0 & -\frac{k_i}{L_0 + L_x} & \frac{-R}{L_0 + L_x} \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \frac{1}{L_0 + L_x} u \quad \text{and} \quad (3.20)$$

$$y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ i \end{bmatrix}, \quad (3.21)$$
which is the linearised state space of equations (3-11) and (3-16). Complying with this requirement changes the input variable. Analysis of the system equations show that voltage should be the input variable.

where \( L_0 = \frac{K}{2x_0} \) in equation (3-16). The Laplace transform of equation (3-11) with \( i \) substituted from equation (3-16) gives the following position-voltage transfer function

\[
\frac{X(s)}{U(s)} = \frac{k_i}{m} \frac{s + \frac{k_i}{m}}{(L_0 + L_x)s^3 + Rs^2 - 2L_x k_i s - 2R k_x}. \tag{3.22}
\]

The controller model described in this dissertation is using the following parameters of an existing system set up used by Vischer [46]:

\[
m = 0.75 \text{kg}, \quad x_0 = 2 \text{mm}, \quad L_x = 70 \text{mH}, \quad L_0 = 40 \text{mH},
\]

\[
k_i = 11 \frac{N}{A}, \quad k_x = 1.1 \frac{kN}{m}, \quad R = 4 \Omega, \quad i_0 = 0.5 \text{A}.
\]

The open loop step response of the continuous system model is depicted in figure 3-7. The levitated rotor is unstable. The rotor is moving towards the magnet with an increasing velocity caused by the increasing magnetic force.
This continuous system would have been stable if all the poles were contained in the left half-plane. This system (figure 3-8) is unstable as the pole in the middle falls to the right half plane (figure 3-9 shows the descritized model with coordinates).
The model is discretized using $\mathbf{A}_d = \mathbf{I} + \mathbf{A}_c T + \mathbf{A}_c^2 T^2 / 2! + \ldots$, $\mathbf{B}_d = \left( \mathbf{I} + \mathbf{A}_c T + \mathbf{A}_c^2 T^2 / 2! + \ldots \right) \mathbf{B}_c$, and $\mathbf{C}_d = \mathbf{C}_c$ where $T$ is the sampling time in seconds. The MATLAB function ($c2dm$) was used to convert the continuous state-space to discrete state-space, sampling method and sampling time were specified as zero order hold and 1 ms respectively. The discrete state-space equations are given by

$$\mathbf{x}(k + 1) = \mathbf{A}_d \mathbf{x}(k) + \mathbf{B}_d u(k),$$

and

$$y(k) = \mathbf{C}_d \mathbf{x}(k) + \mathbf{D}_d u(k).$$

(3.23) (3.24)

The sampled-data system is stable if all the poles lie within the unit circle. See figure 3-9 for the discrete pole-zero plot. Analysis of the plot shows that the system is marginally stable. The poles are $p_{1,2,3} = 1, 0.968 \pm j 0.028$.

![Pole-Zero Map](image.png)

Figure 3-9: Discrete open loop pole-zero plot.
3.7 AMB controller modelling and optimisation

Control theory offers various control design methods for systems in state variable form. The main advantage of such methods is their applicability to any linear systems given by a controllable matrix pair $A_d$ and $B_d$ matrices. With pole placement, the feedback control is determined in such a way that the dynamics of the closed loop system has the desired time response and damping. Sampling the signal according to the minimum sensor frame period $T = 1 \text{ ms}$ (in section 3.4.2), a discrete state variable representation is obtained,

$$x(k + 1) = A_d x(k) + B_d u(k)$$

$$= \begin{bmatrix} 1.001 & 0.001 & 0.000 \\ 1.467 & 1.000 & 0.014 \\ -0.073 & -0.098 & 0.964 \end{bmatrix} x(k) + \begin{bmatrix} 0.0000 \\ 0.0001 \\ 0.0089 \end{bmatrix} u(k), \text{ and} \quad (3.25)$$

$$y(k) = C_d x(k) + D_d u(k)$$

$$= \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} x(k). \quad (3.26)$$

In the model $x_1(k)$ is the position of the rotor, which is measured by the CCD position sensor. The state variable, $x_2(k)$, is the rotor velocity $\dot{x}$ and $x_3(k)$ is the electric current flowing in the electro magnet.
3.7.1 Linear quadratic optimal control

A design technique for optimal linear regulator control systems with quadratic cost function was developed. The closed loop equation is given by

$$x(k+1) = (A - BK)x(k),$$  \hspace{1cm} (3.27)

where \( K \) is the feedback gain. The optimal design procedure minimizes the following cost function

$$J_N = \sum_{k=0}^{N} m(k),$$ \hspace{1cm} (3.28)

$$m(k) = x^T(k)Q(k)x(k) + u^T(k)R(k)u(k),$$ \hspace{1cm} (3.29)

with

$$N = \infty, \quad Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad R = 1.$$ \hspace{1cm} (3.30)

\( Q \) is chosen such that when minimizing the quadratic function, the diagonal matrix equally weigh the position \((x_1(k))\), velocity \((x_2(k))\) and current \((x_3(k))\). The magnitude of the state \(x_1(k)\) is minimized without regard to \(x_2(k)\), while on the other hand \(x_2(k)\) is determined by its relationship to \(x_1(k)\). \( R \) is the weight of the control and is added to the cost function to limit \(u(k)\) to realizable values for example in the study current is the main concern. The feedback matrix gain was calculated as \([33]\)
\[ K(k) = w(k)B^TP(k+1)A \quad (3.31) \]

\[ w(k) = \left[ B^TP(k+1)B + R \right]^{-1}, \quad \text{and} \]

\[ P(k) = A^TP(k+1)[A - BK(k)] + Q. \quad (3.33) \]

Taking the iterations \( N = 400 \), where \( P(400) = Q \), the feedback matrix gain \( K \) was calculated to be \( [1412.7 \quad 27.603 \quad 6.2279] \). The closed loop system characteristic equation is given by

\[ \alpha(z) = |zI - (A - BK)| \quad (3.34) \]

\[ = z^3 - 2.9069z^2 - 2.8174z - 0.9105. \quad (3.35) \]

The poles are \( [p_1 \quad p_2 \quad p_3] = [0.9717 \quad 0.9676 + j0.0275 \quad 0.9676 - j0.0275] \), the gain matrix did not change the zeros, only the pole that was outside the unit cycle has been brought inside the circle. See figure 3-10 for the pole-zero plot. See figure 3-11, for an initial condition response of the closed-loop system, with the initial conditions \( x_{1,2,3}(0) = [0 \quad 0 \quad 0] \) and the reference rotor equilibrium position set at 2.5 mm. The system has been optimally stabilized as it efficiently reaches equilibrium position shown in figure 3-11.
Figure 3-10: Stabilized pole-zero plot of the discrete function.

Figure 3-11: Step response with equilibrium reference set at 2.5mm.
3.7.2 Kalman Filter Optimal State Estimation

Measuring all the plant variables is impractical. It is practical to measure the rotor position but not the rotor velocity or oscillation. A technique for estimating plant states from the available information is used. The system that estimates states of another system is called an observer. The states of the system to be observed (See figure 3-12) are $x(k)$, the states of the observer are $q(k)$ and it is desirable that $q(k)$ be approximately equal to $x(k)$.

Velocity is estimated from observing the velocity $\dot{x}$ and it can be defined as the rate of change of the rotor from a reference position. The observer is designed, after deciding an appropriate characteristic equation is in place. By sampling the position of the rotor and determining whether it is a positive displacement or negative displacement, the rate of change of the polarity could give the oscillation of the rotor. When the rotor is moving upwards its velocity is taken as positive, and when it moves down its velocity is taken as negative.

![Figure 3-12: State estimation illustration.](image-url)
The Kalman filter for the observer was used. The Kalman Filter is a set of mathematical equations that provide an efficient recursive computational means to estimate the state of a process. The estimates of states $\mathbf{x}(k)$ are the a priori state estimate denoted as $\mathbf{q}(k)$ and a posteriori estimate denoted as $\mathbf{q}(k)$. The a priori and posterior estimate errors are

$$\mathbf{e}(k) = \mathbf{x}(k) - \mathbf{q}(k),$$

and

$$\mathbf{e}(k) = \mathbf{x}(k) - \mathbf{q}(k).$$

The a priori estimate error covariance is then

$$\overline{\mathbf{P}}(k) = E [\mathbf{e}(k)\mathbf{e}^T(k)].$$

and the posterior estimate error covariance is given by

$$\mathbf{P}(k) = E[\mathbf{e}(k)\mathbf{e}^T(k)].$$

Hence the diagonal elements of $\mathbf{P}(k)$ are the average squared errors of the estimation. The cost function for the minimization process is chosen as the trace of $\mathbf{P}(k)$. The resulting Kalman filter equations are

$$\mathbf{q}(k) = \mathbf{q}(k) + \mathbf{G}(k)[\mathbf{y}(k) - \mathbf{Cq}(k)],$$

and

$$\overline{\mathbf{q}}(k+1) = \mathbf{Aq}(k) + \mathbf{Bu}(k).$$
In this equations, $\bar{q}(k)$ is the predicted state estimate at the sampling instant at $k$. The gain matrix $G(k)$ is the Kalman gain, and is calculated from the covariance equations,

\begin{equation}
G(k) = \bar{P}(k)C^T[CP(k)C^T + R_{nn}]^{-1}, \tag{3.42}
\end{equation}

\begin{equation}
P(k) = [I - G(k)C]\bar{P}(k), \text{ and} \tag{3.43}
\end{equation}

\begin{equation}
\bar{P}(k + 1) = AP(k)A^T + Q_{nn}. \tag{3.44}
\end{equation}

In this equation, $P(k)$ is the covariance of the prediction errors or the $a priori$ estimate covariance error,

\begin{equation}
\bar{P}(k) = E[\bar{e}(k)\bar{e}^T(k)], \tag{3.45}
\end{equation}

where

\begin{equation}
\bar{e}(k) = x(k) - \bar{q}(k). \tag{3.46}
\end{equation}

$R_{nn}$ is the measurement noise covariance usually measured prior to operation of the filter. The determination of the process noise covariance $Q_{nn}$ is generally more difficult as it is typically not possible to directly observe the process being estimating.
In either case, whether or not rational basis for choosing the parameters is available, often times superior filter performance (statistically speaking) can be obtained by tuning the filter parameters \( R_{mn} \) and \( Q_{pn} \). The tuning is usually performed off-line, frequently with the help of another (distinct) Kalman filter in a process called system identification. Noting also that under conditions where \( Q_{pn} \) and \( R_{mn} \) are in fact constant, both the estimation error covariance \( P(k) \) and the Kalman gain \( G(k) \) will stabilize quickly and then remain constant. Using MATLAB taking 400 iterations with the assumptions that,

\[
Q_{pn} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \ \text{and} \ \ R_{mn} = 1. 
\]

The Kalman gain was calculated to be

\[
G(k) = \begin{bmatrix} 0.6186 & 0.6115 & -0.1319 \end{bmatrix}. 
\]

In the filter equations (3.40 and 3.41), the predicted estimate \( \bar{q}(k) \) can be eliminated, resulting in

\[
q(k) = [A - G(k)CA]q(k-1) + [B - G(k)CB]u(k-1) + G(k)y(k),
\]

where \( y(k) \) is the measurement and

\[
u(k-1) = -Kq(k-1).
\]
Substituting (3.51) in equations (3.50) result in

\[ q(k) = \left[ A - G(k)CA - B + G(k)CB \right] q(k-1) + G(k)y(k). \] (3.52)

Hence the control-estimator transfer function, namely

\[ D_{ce}(z) = -\frac{U(z)}{Y(z)}, \] (3.53)

together with

\[ U(z) = -K(zI - A + BK + GC)^{-1}GY(z), \] (3.54)

gives

\[ D_{ce}(z) = zK[zI - A + GCA + BK - GCBK]^{-1}G. \] (3.55)

Figure 3-14, illustrates the closed loop system with a sensor and the digital controller.
Figure 3-13 shows the control system designed by linear-quadratic optimal procedure and using the state gains, in addition, the steady-state Kalman filter is employed to estimate the states. The design is called the infinite-horizon linear-quadratic-Gaussian (IH-LQG) design.

![Figure 3-14: IH-LOG control system [33].](image)

If there are no plant disturbances \((Q = 0)\), the steady-state Kalman filter will completely ignore the measurements \((G(k)=0)\). Conversely, if the disturbances on the plant are large, the resulting value of \(G(k)\) will increase the effects of the measurements on the state estimates, and \(U(z)\) and the plant dynamics will have effect. In some cases \(R_{\text{mod}}\) is purposely increased to indicate model uncertainty.

Figure 3-15 shows the estimated state step response and the actual state step response. The first 0.13 s of the actual velocity graph depicts that the rotor accelerates upwards. This is because of the rotor displacement error to the reference equilibrium position. Deceleration of the rotor starts at
about 0.03 m/s and stabilises at 0 m/s after 0.4 s. The velocity becomes 0 m/s because the rotor has reached the equilibrium position where it is stable.

![Figure 3-15: Estimated and actual states step response.](image)

The experimental measurement results in chapter 5 are considered in this section and the worst case noise variance of the different measurements trials is introduced. Substituting the variance of the measurement as the measurement noise \( R_{nm} \) in the Kalman gain equation (3.42), the new observer gain is calculated to compensate for the error caused by the sensor noise.

The means, variances and standard deviation for the different position measured from one of the method used (described in detail in chapter 5 section 5.3) were: position 1 \( \mu = 0.3424 \), \( \sigma^2 = 2.1782 \times 10^{-4} \) and \( \sigma = 0.0148 \), position 2 \( \mu = 0.4990 \), \( \sigma^2 = 1.0959 \times 10^{-4} \) and \( \sigma = 0.0105 \), position 3 \( \mu = 0.8512 \), \( \sigma^2 = 1.8929 \times 10^{-5} \) and
\( \sigma = 0.0044 \) and position 4, \( \mu = 1.1894 \), \( \sigma^2 = 4.3290 \times 10^{-4} \) and \( \sigma = 0.0208 \). The worst case noise variance was position 4 \( \sigma^2 = 4.3290 \times 10^{-4} \). Figure 3-16 shows the step responses when taking into consideration the measurement noise variance from the measured position. The dotted plot is the reference actual velocity state graph and the blue velocity graph is the observed state plot. In the figure 3-16 there is no visible difference when compared with figure 3-15. This may be due to the implementation of the Kalman filter to optimally observe the velocity with the error parameter accounted \( (R_{nn} \text{ see equation 3.42}) \). During the first few iterations in figure 3-16 and figure 3-15 the observed and estimated plots are visibly different from each other but became similar as the error decreases to zero. The error is ultimately compensated for and hence the velocity stabilizes to zero.

Figure 3-16: Velocity step response with measurements error variance accounted.
Chapter 4

Methods and Materials

4.1 Introduction

The content of this chapter gives a detailed description of the experimental set-up, measurements procedures and methods used to achieve the measurements. Mechanical experimental set-up are presented and the description of how measurements were taken. The microprocessor used to process the measurements is described including the algorithm used to accurately measure the displacement of the rotor. The two experimental setup assembled are explained in section 4.2 and section 4.3.

4.2 First experimental set-up

Figure 4-1 is the experimental set-up built to experiment with two-dimensional simultaneous measurements using a single colour CCD, using the red and green laser as shown in figure 3-1.
The drum representing the rotor is held into position by four elongated springs, two on-top and two on the bottom. The displacing screws limit the axial and radial movements. Figure 4-2 shows the horizontal and vertical displacing vices and figure 4-3 shows the mounted CCD and the FPGA board. The displacing screw threads are pitch 2 mm. By turning the holder one cycle the rotor will be displaced by two millimetres. The displacement is indicated by a steal pointer on a plate with eight quadrants. Calibrating both the laser beam and the rotor position sets a reference position.

Fine-tuning of the rotor displacement is possible by further dividing the quadrants of the displacers. The mirrors are held in position by a flexible metal rod normally used for adjustable study table lamps. A measuring set point is set in such a way that the laser beams are close to the drum and that the CCD sensor detects any slight movements. The movement of the shaft is set in such a way that it does not touch the mirrors.

Figure 4-2: Manual displacement method.  Figure 4-3: FPGA DSP board.
The types of lasers used are laser pointers using laser diodes. Laser diodes should not be operated continually for more than 3 minutes without a cooling fan or heat sink fitted to the lasers diode casing. The lasers are held in position by vice tubes. The vice tubes are tightened in such a way that they can be adjusted, to allow calibration of the laser beams and the rotor.

The horizontally pointed laser is adjusted vertically until the beam is tangent to the rotor and the vertically pointed laser is adjusted horizontally until the beam is tangent to the rotor. The laser pointers and deflecting mirrors are mounted on the same frame together with the CCD, thereby minimising the frame vibration in affecting the measurements. Natural vibrations of the metal frame, table and floor are not accounted for in the experiment though it will contribute noise to the measurements made.

The lenses used are plano-concave having a diameter of 3 mm and an effective focal length of 6 mm. They are coated with an anti-reflection coating $MgF_2$. The mechanical set-up lenses are separately fixed in a holder, this allows a flexible adjustments and an angle tilt to enable the beam to pass through the lens at 90 degrees. The lenses receive the beam deflected by the mirrors. Lenses are adjusted in such a way that the beam reaching the CCD sensor passes through the lens and the beam is expanded up to the length of the active pixels for optimum CCD resolution.
4.3 Second experimental set-up

Figure 4-4 shows the experimental set-up used to analyse the characteristics of the CCD response and noise measurements. A micro-metre with a resolution of 0.01 mm was used to displace a plate, which shadowed a 2 mm laser beam. This set-up was using a Xilinx® FPGA software integrated logic analyser to analyse the real-time signal logic and the measurements on the FPGA data output ports.

There is a difference between the implementation of the two experimental set-ups shown in figure 4-1 and figure 4-4. In figure 4-1 the self-made displacing screws unevenly displaced the rotor, because of the inaccurately polished surfaces between the displacing screw and the rotor. Figure 4-4 set-up used the micro-metre which is more accurate than the installed rotor displacing screws. Figure 4-4 setup was constructed to analyse the CCD noise characteristics and to eventually achieve high measurements accuracy while figure 4-1 was build to achieve the design shown in figure 3-1.

Figure 4-4: Micro-metre CCD noise characteristics test in an optical table.
The laser beams should focus on the CCD sensor as the target and the laser beams are supposed to be 22 mm in diameter at the point they reach the sensor. The lenses can be adjusted to move away from or closer to the sensor to accommodate the laser expansion. The input beam width represents the measuring range (See figure 4-5 and table 4-1). Distance $d_1$ and $d_2$ is the distance of the sensor corresponding to the beam width $R_{o_1}$ and $R_{o_2}$ respectively. The equation (derived from equation 3.4) demonstrates how the distance between the lens and the sensor varies with the input laser beam width,

$$d_f = f \times \frac{R_i}{R_o},$$ \hspace{1cm} (4.1)

where $f$ is the effective focal lens and $d_f$ is the distance with reference to the focal lens.

Figure 4-5: CCD displacement with input range.
After having the fixed range $R_o$ (beam width) as the reference of measurement and calibrated the displacement of the CCD from the lenses specifications, the measurements from the sensor were recorded. The displacement of the rotor in millimetres ($mm$) can be calculated by,

$$M = R_o \frac{P_{no}}{2700},$$

(4.2)

where $M$ is the measured displacement in $mm$, $R_o$ is the displacement range, $P_{no}$ is the measured active pixel position and 2700 is the total number of pixels that are processed.

<table>
<thead>
<tr>
<th>$R_o$</th>
<th>$R_f$</th>
<th>$f$</th>
<th>$d_f$</th>
<th>$d = f + d_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>22 mm</td>
<td>-6 mm</td>
<td>132 mm = 13,2 cm</td>
<td>124 mm = 12,4 cm</td>
</tr>
<tr>
<td>2 mm</td>
<td>22 mm</td>
<td>-6 mm</td>
<td>66 mm = 6,6 cm</td>
<td>60 mm = 6 cm</td>
</tr>
<tr>
<td>3 mm</td>
<td>22 mm</td>
<td>-6 mm</td>
<td>44 mm = 4,4 cm</td>
<td>38 mm = 3,8 cm</td>
</tr>
<tr>
<td>0.5 mm</td>
<td>22 mm</td>
<td>-6 mm</td>
<td>264 mm = 26,4 cm</td>
<td>258 mm = 25,8 cm</td>
</tr>
<tr>
<td>0.25 mm</td>
<td>22 mm</td>
<td>-6 mm</td>
<td>528 mm = 52,8 cm</td>
<td>522 mm = 52,2 cm</td>
</tr>
<tr>
<td>0.1 mm</td>
<td>22 mm</td>
<td>-6 mm</td>
<td>1320 mm = 132 cm</td>
<td>1314 mm = 131,4 cm</td>
</tr>
</tbody>
</table>
4.4 FPGA data processing

The FPGA DSP board implements the software part of the project. The software is divided into three modules: the control module, the arithmetic module and the synchronising module. The control module generates all the driver waveforms for the CCD and the ADC. Counters are implemented to determine the periods and the waveform pattern of the driving clocks. The arithmetic module does all the calculations required to process the image pixel data. The synchronising module supplies the master clock for all the other module activities including the counters.

Synchronisation of the FPGA clock signals and the ADC signals makes it possible to locate a particular pixel in the CCD array which is being processed at that moment. A counter implemented in the software provides a value which locates the pixel in the CCD. The advantage of using FPGA is that calculations are done in a single cycle by parallel execution of instructions. The same FPGA executing measurement instructions can be used in future to implement the AMB controller function, using MATLAB® DSP functions.

The data is captured from the CCD sensor through the ADC to the FPGA (figure 4-6). The signal from the sensor is connected to the FPGA DSP board by SMA connectors to minimise interference (See figure 4-3). The logic analyser is used to analyse the CCD signal which represents the position. The logic analyser also shows the clock signals driving the CCD sensor. The interfacing ports are for measurement analysis and also for other control signals e.g. mode selection especially for environmental adaptation.
The challenging task in this configuration is to filter out noise or cross talk from the data bus wires. Higher frequency clock signals can be seen coupled in low frequency control signals. Different frequency channels can be isolated by using shielded data cables. Harmonics are also noticeable on the CCD power supply when the CCD detects a sharp image; such problems are caused by circuit board design. When the CCD dynamically draws current it causes the voltage level to fluctuate.

![Figure 4-6: Complete system block diagram configuration set-up.](image)

Software for the FGPGA is written in VHDL (Very High Speed Integrated Circuit Hardware Descriptive Language). Several software algorithms were written to convert the rotor image on the CCD to a rotor position. Two algorithms were implemented. The first algorithm analyse the image pixels based on a stored default pixel value. The second algorithm analyses the image pixels based on the threshold pattern formed by the rotor image edge. Implementing the algorithm that uses the default method, the ADC data (Data_in) is compared with a default value (Default) stored (see figure 4-7). In a register, if the data is less than the default it is stored as a new default and the pixel number (Pixel_no), which is the counter value at that pixel location, is stored. The end of cycle
(ROG = ‘1’) is checked, which simply means that when it is high all the pixels values are processed. Figure 4-7 is the flow diagram summarising the measurement procedures followed to read and manipulate the digital signal from the ADC using the default algorithm.

Figure 4-7: Program flow diagram.
The counter value that corresponds to the pixel number is compared with the previous achieved output (Prev_pixel_no) of the previous cycle. The ADC samples the CCD signal on the rising edge of the encode signal. The comparison simply checks if the new pixel number is within $\pm 2$ of the previous pixel number and if it is within the limit the output value will not change, but it will remain the previous pixel number; if it is outside the limit the new value will be assigned. This comparison is necessary to eliminate unstable output, though it reduces the resolution of the system. The $\pm 2$ is a variable that can be increased or reduced depending on the level of the noise.

Implementing the algorithm that uses the threshold method (the threshold was selected from a number of random values between 10 and 200), the threshold is selected to differentiate between the shaded pixels and the illuminated pixels. The image pixels which are not exposed to a laser beam will produce a value of 255 from the eight bit ADC while the ones exposed will produce values ranging from 4 to 112 depending on the laser beam intensity. The threshold adaptable to different environments and dynamic laser intensities was the value 150. Converted pixels values are compared to a threshold value. The last counter pixel value to be less than 150 is saved, which identifies the pixel position on the CCD. The method discussed uses all the pixels of the CCD as the maximum pixels usage gives an optimal resolution of the CCD sensor; this is possible without introducing an image lag as the frame rate is set considering the optimal maximum speed of the CCD.
Chapter 5

Experimental Results

5.1 Introduction

This chapter is about the experimental measurement results. The experimental results are presented, analysed and discussed. The measurement error is analysed as well as its effect on the optimal control of the AMB.

5.2 CCD responses and tests executed

Figure 5-1 shows the CCD response to a measured position. The pixels which were exposed to a laser beam were unstable in a frequency equivalent to the clock driving the CCD while the pixels which were not exposed (shaded) to a laser beam were stable with a constant voltage charge.

Figure 5-1: CCD response of a measured position.
5.2.1 Interference test

This experiment was done with the purpose of analysing the effect of the two lasers interfering with each other in their respective sensitive line arrays. Another purpose was to analyse the effect a change in the environment. Figure 5-2 shows two lasers (the red and green laser beams) intersecting on the CCD.

The CCD behaviours that were observed are:

- The green and the red lasers did not interfere with each other on their respective line arrays when the laser beams were expanded.
- The higher intensity of the green laser beam visibly affected the 620 nm CCD pixels line array response.
- With the white light filter installed in front of the CCD, laboratory lights did not affect the CCD response.

Figure 5-2: Beam image translation experiment.
5.2.2 Experimental set-up and test connection

Two types of test setups were experimented with as explained in section 4.2 and section 4.3. One with the complete two-dimensional optical components and the other with a single axis configuration. Figure 5-3, shows the circuit block diagram of the double axis measurement experiment setup. The rotor displacement translation on the beam was responding by fading after its deflection by the mirrors. This was because glass mirrors were used instead of metallic mirrors; this was even more evident when a double image was formed on the CCD. Glass mirrors causes double images because of two reflections with different reflective indices. The first reflection is between the air and the glass and the other between the glass and the glass coating (in figure 5-2). It was also realized that by eliminating the mirrors the set-up would be more reliable. A new set-up without mirrors was designed for accurate measurements to be taken as shown in figure 4-4.
5.3 Experimental results

Measurement trials were conducted for different positions and some of the measurement results that were recorded are shown in appendix A, table A-1. The CCD reading is converted to displacement in millimetres by

\[ M = R_o \frac{P_{no}}{2700}, \]  

(5.1)

where \( M \) is the displacement in millimetres, \( R_o \) is the measurement range (2 mm), 2700 is the total number of pixels being sampled and \( P_{no} \) is the value being read which locates a pixel in the CCD array. Figure 5-4 shows the logic states from a Chipscope (FPGA integrated logic analyser). The first trace in figure 5-4 Input_data is the input data from the ADC to the FPGA. The second trace Out_data is the output data from the FPGA representing the calculated position. The third is ROG, following Reset, Encode Q1 and Q2 are drivers explained in section 3.5.2 and section 4.4.
Measurement trials were conducted for different positions of the CCD, and the position measurements at those positions were recorded and analysed. Figure 5-5 shows the histograms plots with a fitted Gaussian distribution. The plot is to analyse the data distribution type. The more samples acquired the clearer the true distribution of the noise will become in the histogram plot. The measurement process was automated to capture a thousand samples per position using hyper terminal. The captured data was stored as a text file.

Figure 5-4: Chipscope logic analyser.
The noise present in the measurements is assumed to be zero, mean Gaussian noise with unknown variance to be inferred from the measurements. Recall that the (statistical) mean, in the ergodic case, is the time average whereas the variance is the power of the AC component of a signal.

The mean of the measurement distribution is derived from

\[ \mu_{x+\varepsilon} = E(x) + E(\varepsilon), \]  

(5.2)

where \( E(x) \) is expectation of the deterministic signal (i.e. the measured position) and \( E(\varepsilon) \) is the expectation of the measurement noise. Above the assumption was that that \( E(\varepsilon) = 0 \). Therefore \( \mu_{x+\varepsilon} = \mu_{\varepsilon} \) and it will be noted only as \( \mu \).

The variance of the measurement distributions consists of two components namely \( \sigma^2_{\varepsilon} \) the variance of the noise and \( \sigma^2_{x} \) the variance of the deterministic signal. It is a fact that the variance of any deterministic signal is zero, i.e. \( \sigma^2_{x} = 0 \). This is true for the used setup as measurement uncertainties were eliminated by performing experiments on a stabilised table. Therefore

\[ \sigma^2_{x+\varepsilon} = \sigma^2_{\varepsilon}, \]  

(5.3)

holds where \( \sigma^2_{\varepsilon} \) will be noted only as \( \sigma^2 \).

A multidimensional unconstrained minimization (MATLAB routine listed in appendix C) was used to find the optimal estimate in the mean squared error sense of the mean and
variance of the position measurements separately for each position considered. Referring to this as method 1. The Mean Squared Error (MSE) and the Normalised Mean Squared Error (NMSE) are defined as

\[ NMSE = \frac{MSE}{\frac{1}{n} \sum_{i=1}^{n} x_i^2} \]  

(5.4)

where \( x_i \) is the measurements data and \( n \) is the number of samples taken. Calculations are listed in table 5-1.

Figure 5-5 shows the histogram plots of the four positions measured and with the Gaussian noise distribution fitted. The data distribution in figure 5-5 resembles a gaussian distribution, but due to short data records there has not been convergence of the histograms. The fits signifies that the noise is Gaussian and therefore the variance, can be used in the Kalman Filter to compensate the sensor characteristic noise. Table 5-1 shows the estimated means, variances and standard deviations of the fitted Gaussian indicated under method 1. The mean change in figure 5-5 is due to the different positions measured.
To verify the above results another approach was considered for calculating the mean and variance of the measurements namely

\[
\mu = \frac{1}{n} \sum_{i=1}^{n} x_i , \quad \text{and} \\
\sigma^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \mu)^2 ,
\]

(5.5)  

(5.6)
where $x_i$ is the measurements data and $n$ is the number of samples taken. Referring to this as method 2. Table 5-1 shows calculated means and variances under method 2. Comparing the means of the two methods they differ less while the variances tend to differ more with corresponding measured position.

Figure 5-6 depicts the measurement distribution for the four measurement position taken. The measured data in the different segments of the CCD produces noise with different noise variances. The difference in the Gaussian mean is because four different positions were measured. For the simulation involving the Kalman Filter, the worst case was decided namely the noise variance $\sigma^2 = 4.3290 \times 10^{-4}$. Figure 5-6 shows clearly the differences in the noise variances between the four measured positions which might have caused by the CCD pixel non-uniform charging.

Implementation of the Gaussian distribution analysis in the AMB mathematical model was done in the last section of chapter 3 by using the worst case variance of the measured position to replace the noise parameter in the Kalman filter.
Figure 5-6: Fitted Gaussian distribution of the four measurements positions.

Table 5-1: Summary of means and variances of the measurements.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Position 1</th>
<th>Position 2</th>
<th>Position 3</th>
<th>Position 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu )</td>
<td>Method 1: 0.3426</td>
<td>0.4969</td>
<td>0.8509</td>
<td>1.1898</td>
</tr>
<tr>
<td></td>
<td>Method 2: 0.3424</td>
<td>0.4990</td>
<td>0.8512</td>
<td>1.1894</td>
</tr>
<tr>
<td>( \sigma^2 )</td>
<td>Method 1: (2.5829 \times 10^{-4})</td>
<td>(9.9348 \times 10^{-5})</td>
<td>(1.7346 \times 10^{-5})</td>
<td>(6.3165 \times 10^{-5})</td>
</tr>
<tr>
<td></td>
<td>Method 2: (2.1782 \times 10^{-4})</td>
<td>(1.0959 \times 10^{-4})</td>
<td>(1.8929 \times 10^{-5})</td>
<td>(4.3290 \times 10^{-5})</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Method 1: 0.0161</td>
<td>0.0100</td>
<td>0.0042</td>
<td>0.0079</td>
</tr>
<tr>
<td></td>
<td>Method 2: 0.0148</td>
<td>0.0105</td>
<td>0.0044</td>
<td>0.0208</td>
</tr>
<tr>
<td>( MSE )</td>
<td>(3.2949 \times 10^3)</td>
<td>(4.2438 \times 10^3)</td>
<td>(3.9109 \times 10^3)</td>
<td>(766.782)</td>
</tr>
<tr>
<td>( NMSE )</td>
<td>(2.8057 \times 10^4)</td>
<td>(1.7033 \times 10^4)</td>
<td>(5.3978 \times 10^4)</td>
<td>(541.863)</td>
</tr>
</tbody>
</table>
Chapter 6

Conclusions and recommendations

6.1 Conclusion

The focus of the project was to build and implement a two-dimensional position sensor system applicable to an AMB. The sensor had to be capable of withstanding the dynamic noise and magnetic interferences of the AMB system. An optimal controller for the AMB was modelled and simulated using existing AMB parameters and the sensor variance derived from the measured results. The AMB controller model implemented an optimal linear quadratic controller to stabilise the system. The Kalman filter reduced the effect of noise in the system. Thus the system states were optimally observed as the predicted states with the noise variance produced a response showing that the noise was filtered out. The experimental set-up was designed and constructed. A VHDL program suitable for taking measurements was implemented. Measurements of the rotor displacement were taken. The variances of the measurement errors were implemented in the system through the Kalman filter to eliminate the measurements noise effect on the system. Due to the position dependent variance of the measured noise, a Kalman Filter does not perform optimally to a real life because the derivation of a Kaman Filter assumes that the noise is wide sense stationary.
6.2 Recommendations for future work

- Developing and testing different software algorithms because of its significance in calculating the position.
- Implementing a software algorithm that compensates for the rotor surface and changes in ambient light.
- Using a high speed CCD for a higher frame rate.
- This type of experiment could be quicker and easier if it could be done using an optical setup table, rather than building a mechanical setup.
- Conversion of CCD pixels charge to digital data affect the accuracy of the CCD sensor system. Therefore an ADC with a matching voltage level should be used.
- CCD I/O signals are easily affected by clock jitter and harmonics induced by command signals with different frequency. Therefore a properly designed circuit is needed with noise compensated for.
- Using a light filter to compensate for ambient light and high laser intensity.
- The image edge response of the pixels representing the position has to be characterized to differentiate it from other noise which tends to imitate the image edge pattern response.
- Implementation of quality designed beam manipulators. Beam manipulators provide precise, independent, stable control over beam translation and angle. They precisely bend or translate a laser beam to achieve sub-nanometre measurements, reducing laser beam alignment measurement errors.
6.2.1 Recommendation modifications: option 1

Figure 6-1, the horizontal (x) displacement is given by the x-region, which is the shaded part of the line array pixels. The movement of the rotor horizontally (backward and forward) will shorten and lengthen the x-region respectively. The amount of pixels in the x-region gives the magnitude of the x-region, which can be translated to the horizontal (x) displacement of the rotor. The length of the x-region will be directly proportional to the displacement of the rotor from a set-point (zero point). In summary the pixels that are not exposed to the light gives the horizontal (x) displacement of the rotor.

![Figure 6-1: New method measurement.](image)

The vertical displacement can simply be derived from the pixels which are exposed to the light. Divide the CCD pixels into two equal regions, $Y_1$ (upper part) and $Y_2$ (lower part). These regions will always be exposed to a certain quantity of light. While the vertical displacement is in the set-point the two regions should have equal exposure to light.
Assuming the range of the rotor displacement is bounded by a circular electro-magnets, it is conclusive that the calibrated light beams will always represent the displacements. The vertical direction displacement is given by

$$ Y = Y_2 - Y_1, $$

(6-1)

where the polarity will represent whether the rotor goes upwards or downwards. The angle at which the lasers are mounted should be exactly the same, otherwise the proportion in change of the beam width of the two lasers will be unequal.

**Advantages of the method in figure 6-1**

- Deflecting mirrors are eliminated which tend to cause errors.
- A sharp image is achieved without the mirrors.
- Monochrome CCD with a single line array is used.
- Only one type of laser light is required.
- Eliminating the colour CCD, mirrors and the green laser, drastically reduces the cost.

**Disadvantage**

- Software is more complicated than the first method.
6.2.2 Recommendation modifications: option 2

Figure 6-2, two LED adjacent to each other with a distance equal to the rotor diameter emits a light. Two light intensity sensors and LED’s installed opposite to each other separated by the rotor detect the light quantity. The intensity sensors are each directly sensing light from the corresponding LED. When the rotor moves horizontally along the x-axis the intensity of the light received by the sensors will change. The sensor will give a voltage output proportional to the light intensity it receives. Although the light intensity sensor is less sensitive to a CCD sensor but using the amplified differential voltage signal of the two intensity sensors, micrometer sensitivity on the measurements can be achieved. This set-up is more cost effective than the CCD application and is anticipated to be very sensitive in detecting the change in the rotor position.

Figure 6-2: Differential intensity-voltage displacement sensor.
References


Appendices
A.1 Automated recorded measurements results tables.

<table>
<thead>
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Table A-1: Recorded results position 1.
Appendix B

B.1 MATLAB Digital Control System Code

<table>
<thead>
<tr>
<th>State space model</th>
<th>Optimally stabilised system code</th>
</tr>
</thead>
</table>
| \begin{align*}
  k_x &= 1100; \\
  k_i &= 11; \\
  m &= 0.75; \\
  L_0 &= 0.04; \\
  L_x &= 0.07; \\
  R &= 4;
\end{align*} |
| \begin{align*}
  A_f &= A-B*KK; \\
  &\text{axis equal;} \\
  &\text{pzmap(ss(A_f,B,C,D,Ts)))} \\
  &[P,Z]=\text{pzmap(ss(A_f,B,C,D,Ts)))} &\%\text{stable plot}
\end{align*} |

<table>
<thead>
<tr>
<th>Kalman filter gain code</th>
<th>Kalman filter gain code with variance</th>
</tr>
</thead>
</table>
| \begin{align*}
  \text{Qpn} &= \begin{bmatrix} 1 & 1 & 1; 1 & 1 & 1 \end{bmatrix}; \\
  R &= 1; \\
  M &= \begin{bmatrix} 1 & 0 & 0; 0 & 1 & 0; 0 & 0 & 1 \end{bmatrix}; \\
  N &= 1000; \\
  &\text{disp('k Gains')} \\
  &\text{for } k = 1:N \\
  &\quad G = M*C'*inv(C*M*C' + R); \\
  &\quad P = M - G*C*M; \\
  &\quad M = A*P*A' + Qpn; \\
  &\text{[k,G']}
\end{align*} |
| \begin{align*}
  \text{Qpn} &= \begin{bmatrix} 1 & 1 & 1; 1 & 1 & 1 \end{bmatrix}; \\
  R_n &= 0.3366; \%\text{ Variance} \\
  M_n &= \begin{bmatrix} 1 & 0 & 0; 0 & 1 & 0; 0 & 0 & 1 \end{bmatrix}; \\
  N &= 1000; \\
  &\text{disp('k Gains')} \\
  &\text{for } k = 1:N \\
  &\quad G_n = M_n*C'*inv(C*M_n*C' + R_n); \\
  &\quad P_n = M_n - G_n*C*M_n; \\
  &\quad M_n = A*P_n*A' + Qpn; \\
  &\text{[k,Gn']}
\end{align*} |

<table>
<thead>
<tr>
<th>Linear quadratic optimal controller code</th>
<th>Linear quadratic optimal controller code</th>
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</table>
| \begin{align*}
  Q &= \begin{bmatrix} 1 & 0 & 0; 0 & 1 & 0; 0 & 0 & 1 \end{bmatrix}; \\
  R &= 10; \\
  N &= 1000; \\
  &\text{P}\text{=}Q; \\
  &\text{disp('k Gains')} \\
  &\text{for } n=1:N \\
  &\quad KK=inv(B'*P*B+R)*B'*P*A; \\
  &\quad P1 = A'*P*(A-B*KK)+Q; \\
  &\quad P=P1; \\
  &\quad k = N-n+1; \\
  &\quad [k,KK]
\end{align*} |
| \begin{align*}
  Q &= \begin{bmatrix} 1 & 1 & 1; 1 & 1 & 1 \end{bmatrix}; \\
  R &= 10; \\
  N &= 1000; \\
  &\text{P}\text{=}Q; \\
  &\text{disp('k Gains')} \\
  &\text{for } n=1:N \\
  &\quad KK=inv(B'*P*B+R)*B'*P*A; \\
  &\quad P1 = A'*P*(A-B*KK)+Q; \\
  &\quad P=P1; \\
  &\quad k = N-n+1; \\
  &\quad [k,KK]
\end{align*} |

\[\text{disp('The Final value of the P Matrix is:')}\]
**Initial condition position states plot**

\[
x_{init} = [0;0;0]; \quad \text{ref} = [0.0025];
\]

\[
I = \begin{bmatrix} 1 & 0 & 0; 0 & 1 & 0; 0 & 0 & 1 \end{bmatrix}; \quad \text{MN} = \text{inv}(I-A+B*KK)*B;
\]

\[
M = \text{inv}(C*MN);
\]

\[
\text{iter} = 500;
\]

\[
\text{Tk} = 0:/\text{iter};(\text{iter}-1)/\text{iter}; \quad \text{Af} = (A-B*\text{K})
\]

\[
\text{for i = 1:iter}
\]

\[
\text{if i == 1}
\]

\[
x(:,1) = \text{Af}*x_{init};
\]

\[
y(1) = C*x_{init};
\]

\[
\text{else}
\]

\[
x(:,i) = \text{Af}*x(:,i-1) + B*M*\text{ref};
\]

\[
y(i) = C*x(:,i-1);
\]

\[
\text{end}; \quad \text{end}; \quad \text{ylim}([0 0.003]); \quad \text{axis}(\text{axis});
\]

\[
\text{stairs}(\text{Tk}, \text{x}(1,:)); \quad \text{grid}
\]

\[
\text{ylabel('position x (m)');}
\]

\[
\text{xlabel('Time(sec)'})
\]

**Estimated initial condition velocity plot**

\[
M2= \begin{bmatrix} 0;1.023;1 \end{bmatrix}
\]

\[
\text{AG = A-G*C*A-B*KK-G*C*B*KK;}
\]

\[
\text{for i = 1:iter; \quad if i == 1}
\]

\[
x1(:,1) = \text{AG}*x_{init} + G*y(1);
\]

\[
x1(:,i) = \text{AG}*x1(:,i-1) + (B-G*C*B)*N*\text{ref} +M2*\text{ref} + G*y(i);
\]

\[
\text{end}; \quad \text{end}; \quad \text{ylim}([0 0.003]); \quad \text{axis}(\text{axis});
\]

\[
\text{stairs}(\text{Tk}, \text{x}(1,:)); \quad \text{grid}
\]

**Estimated initial condition velocity plot with filtered sensor variance error**

\[
\text{AGn} = A-Gn*C*A-B*KK-Gn*C*B*KK;
\]

\[
\text{AGn} = A-Gn*C*A-B*KK+Gn*C*B*KK;
\]

\[
\text{for i = 1:iter}
\]

\[
\text{if i == 1}
\]

\[
x2(:,1) = \text{AGn}*x_{init}+Gn*yk(1);
\]

\[
x2(:,i) = \text{AGn}*x1(:,i-1) + (B-Gn*C*B)*N*\text{ref} +M2*\text{ref} + Gn*y(i);
\]

\[
\text{end}; \quad \text{end};
\]

\[
\text{figure; subplot(2,2,1); stairs(Tk, x(2,:));'-r')}
\]

**Estimated initial condition velocity plot with filtered sensor variance error**

\[
Rn1 = 2.1782e-004; \quad \text{Mn} = \begin{bmatrix} 1 & 0 & 0; 0 & 1 & 0; 0 & 0 & 1 \end{bmatrix};
\]

\[
\text{for k = 1:N,}
\]

\[
\quad \text{Gn} = \text{Mn}*C*inv(C*Mn*C' + Rn1); \quad \text{Pn} = \text{Mn} - \text{Gn}*\text{Mn};
\]

\[
\quad \text{Mn} = \text{A}^*\text{Pn}^*\text{A'} + \text{Qpn}; \quad \text{[k,Gn]};
\]

**Estimated initial condition velocity plot with filtered sensor variance error**

\[
\text{AGn} = A-Gn*C*A-B*KK-Gn*C*B*KK;
\]

\[
\text{for i = 1:iter;}
\]

\[
\text{if i == 1}
\]

\[
x2_1(:,1) = \text{AGn}*x_{init} + G*y(1);
\]

\[
x2_1(:,i) = \text{AGn}*x1(:,i-1) + (B-Gn*C*B)*N*\text{ref} +M2*\text{ref} + Gn*y(i);
\]

\[
\text{end}; \quad \text{end};
\]

\[
\text{Rn2 = 1.0959e-004; for k = 1:N,}
\]

\[
\quad \text{Gn} = \text{Mn}*C*inv(C*Mn*C' + Rn2); \quad \text{Pn} = \text{Mn} - \text{Gn}*\text{Mn};
\]

\[
\quad \text{Mn} = \text{A}^*\text{Pn}^*\text{A'} + \text{Qpn}; \quad \text{[k,Gn]};
\]

**Estimated initial condition velocity plot with filtered sensor variance error**

\[
AGn = A-Gn*C*A-B*KK-Gn*C*B*KK;
\]

\[
AGn = A-Gn*C*A-B*KK+Gn*C*B*KK;
\]

\[
\text{for i = 1:iter;}
\]

\[
\text{if i == 1}
\]

\[
x2_2(:,1) = AGn*x_{init} + G*y(1);
\]

\[
x2_2(:,i) = AGn*x1(:,i-1) + (B-Gn*C*B)*N*ref +M2*ref + Gn*y(i);
\]

\[
\text{end}; \quad \text{end};
\]

\[
\text{figure; subplot(2,2,1); stairs(Tk, x(2,:));'-r')}
\]

**Estimated initial condition velocity plot with filtered sensor variance error**

\[
\text{figure; subplot(2,2,3); stairs(Tk, x(2,:));'-r')}
\]

**Estimated initial condition velocity plot with filtered sensor variance error**

\[
\text{figure; subplot(2,2,4); stairs(Tk, x(2,:));'-r')}
\]
Gaussian distribution plot of the four positions

Position1; Position2; Position3; Position4;

g=[0.2:0.00005:1.3]; [gg,j] = size(g);
x1 = data1*2/2700; x1 = x1(:); %should be column vectors!
N = length(x1); %
u1 = sum(x1)/N; %mean
v_1 = sqrt(v2_1);

for i=1:j,
PG1(i) = 1/(v_1*sqrt(2*pi))*exp((-g(i)-u1).^2)/(2*v2_1));
end;

x2 = data2*2/2700; x2 = x2(:); %should be column vectors!
N = length(x2); %
u2 = sum(x2)/N; %mean
v_2 = sqrt(v2_2);

for i=1:j,
PG2(i) = 1/(v_2*sqrt(2*pi))*exp((-g(i)-u2).^2)/(2*v2_2));
end;

x3 = data3*2/2700; x3 = x3(:); %should be column vectors!
N = length(x3); %
u3 = sum(x3)/N; %mean
v_3 = sqrt(v2_3);

for i=1:j,
PG3(i) = 1/(v_3*sqrt(2*pi))*exp((-g(i)-u3).^2)/(2*v2_3));
end;

x4 = data4*2/2700; x4 = x4(:); %should be column vectors!
N = length(x4); %
u4 = sum(x4)/N; %mean
v_4 = sqrt(v2_4);

for i=1:j,
PG4(i) = 1/(v_4*sqrt(2*pi))*exp((-g(i)-u4).^2)/(2*v2_4));
end;

plot(g,PG1/max(PG1),'y'); grid;
title('Gaussian distribution'); hold on
plot(g,PG2/max(PG2),'r');
plot(g,PG3/max(PG3),'g');
plot(g,PG4/max(PG4));
axis([0.2 1.3 0 1.1]);
text(u1-u1/3,1.08,'Position 1');
text(u1-u1/3,1.04,'mean = 0.3424');
text(u1-u1/3,1.02,'variance = 2.1782e-4');
text(u2-u2/21,1.08,'Position 2');
text(u2-u2/21,1.04,'mean = 0.4990');
text(u2-u2/21,1.02,'variance = 1.0959e-4');
text(u3-u3/15,1.08,'Position 3');
text(u3-u3/15,1.04,'mean = 0.8512');
text(u3-u3/15,1.02,'variance = 1.8929e-5');
text(u4-u4/18,1.08,'Position 4');
text(u4-u4/18,1.04,'mean = 1.1894');
text(u4-u4/18,1.02,'variance = 4.3290e-4');
hold off

[n1,x1_c] = hist(x1,1000);
y1 = sqrt(1/2/pi/v2_1)*exp(-((x1_c-u1).^2)/(2*v2_1));
% gaussian distribution
y1 = y1/(max(y1)); n1 = n1/max(n1);

[n2,x2_c] = hist(x2,1000);
y2 = sqrt(1/2/pi/v2_2)*exp(-((x2_c-u2).^2)/(2*v2_2));
% gaussian distribution
y2 = y2/(max(y2)); n2 = n2/max(n2);

[n3,x3_c] = hist(x3,1000);
y3 = sqrt(1/2/pi/v2_3)*exp(-((x3_c-u3).^2)/(2*v2_3));
% gaussian distribution
y3 = y3/(max(y3)); n3 = n3/max(n3);

[n4,x4_c] = hist(x4,1000);
y4 = sqrt(1/2/pi/v2_4)*exp(-((x4_c-u4).^2)/(2*v2_4));
% gaussian distribution
y4 = y4/(max(y4)); n4 = n4/max(n4);
Histogram Gaussian fitting main function

close all
clear all
[x1,fx1,fxx1,i1] = Gaus_Fit_Pos1; % Function Call for Position 1 fitting calculations
[x2,fx2,fxx2,i2] = Gaus_Fit_Pos2; % Function Call for Position 2 fitting calculations
[x3,fx3,fxx3,i3] = Gaus_Fit_Pos3; % Function Call for Position 3 fitting calculations
[x4,fx4,fxx4,i4] = Gaus_Fit_Pos4; % Function Call for Position 4 fitting calculations

figure;
subplot(2,2,1); % Position 1 Plotting
plot(x1,fx1,'r'), hold on, shg
hold on;
plot(i1,fxx1,'g'), shg
axis([0.25 0.43 0 50]); grid
title('Position 1 Gaussian Distribution Histogram Fit')

subplot(2,2,2); % Position 2 Plotting
plot(x2,fx2,'r'), hold on, shg
plot(i2,fxx2,'g'), shg
axis([0.45 0.6 0 70]); grid
title('Position 2 Gaussian Distribution Histogram Fit')

subplot(2,2,3); % Position 3 Plotting
plot(x3,fx3,'r'), hold on, shg
plot(i3,fxx3,'g'), shg
axis([0.82 0.88 0 120]); grid
title('Position 3 Gaussian Distribution Histogram Fit')

subplot(2,2,4); % Position 4 Plotting
plot(x4,fx4,'r'), hold on, shg
plot(i4,fxx4,'g'), shg
axis([1.11 1.25 0 70]); grid
title('Position 4 Gaussian Distribution Histogram Fit');
hold off

Gaussian fitting position 1 function

function [x,fx,fxx,i] = Gaus_Fit_Pos1()
M = 100; % No. of bins for the histogram
Position1; nn = data1*2/2700; n = nn(:);
m = mean(n); v = cov(n);
[ix, i] = hist(n,M); % Calculate the the histogram
A = sum(fx)*(x(2)-x(1)); % Area under the histogram
fx = fx/A; % Normalise the area under the histogram to unity
a = [x; fx];
p0 = [1; 1]; % Initial values of the Guassian parameters
i = 0.25:0.001:0.45;
% Mean square error fit
p2 = fminsearch(@(p) cost(p,a),p0); % Fit Gaussian to data points using MSE
mse1 = cost(p2,a)
me2 = p2(1); % Mean estimated as obtained from the fitting
ve2 = p2(2); % Variance estimated as obtained fromt the fitting
fxx2 = 1/sqrt(ve2*2*pi)*exp(-(i-me2).^2/2/ve2);

Gaussian fitting position 2 function

function [x,fx,fxx,i] = Gaus_Fit_Pos2()
M = 100; % No. of bins for the histogram
Position2; nn = data2*2/2700; n = nn(:);
m = mean(n); v = cov(n);
[ix, i] = hist(n,M); % Calculate the the histogram
A = sum(fx)*(x(2)-x(1)); % Area under the histogram
fx = fx/A; % Normalise the area under the histogram to unity
a = [x; fx];
p0 = [0; 0.1]; % Initial values of the Guassian parameters
i = 0.46:0.001:0.56;
% Mean square error fit
p2 = fminsearch(@(p) cost(p,a),p0); % Fit Gaussian to data points using MSE
mse2 = cost(p2,a)
me2 = p2(1); % Mean estimated as obtained from the fitting
ve2 = p2(2); % Variance estimated as obtained fromt the fitting
fxx2 = 1/sqrt(ve2*2*pi)*exp(-(i-me2).^2/2/ve2);
**Gaussian fitting position 3 function**

function [x fx fxx2 i] = Gaus_Fit_Pos3()
M = 35; % No. of bins for the histogram
Position3; nn = data3*2/2700; n = nn(:);
m = mean(n); v = cov(n);
fx = hist(n,M); % Calculate the histogram
A = sum(fx)*(x(2)-x(1)); % Area under the histogram
fx = fx/A; % Normalise the area under the histogram to unity
a = [x; fx];
p0 = [0; 0.1]; % Initial values of the Gaussian parameters
i = 0.83:0.0001:0.87;
% Mean square error fit
p2 = fminsearch(@(p) cost(p,a),p0); % Fit Gaussian to data points using MSE
mse3 = cost(p2,a)
me2 = p2(1); % Mean estimated as obtained from the fitting
ve2 = p2(2); % Variance estimated as obtained from the fitting
fxx2 = 1/sqrt(ve2*2*pi)*exp(-(i-me2).^2/2/ve2);

**Gaussian fitting position 4 function**

function [x fx fxx2 i] = Gaus_Fit_Pos4()
M = 100; % No. of bins for the histogram
Position4; nn = data4*2/2700; n = nn(:);
m = mean(n); v = cov(n);
fx = hist(n,M); % Calculate the histogram
A = sum(fx)*(x(2)-x(1)); % Area under the histogram
fx = fx/A; % Normalise the area under the histogram to unity
a = [x; fx];
p0 = [0; 0.1]; % Initial values of the Gaussian parameters
i = 1:0.0001:1.25;
% Mean square error fit
p2 = fminsearch(@(p) cost(p,a),p0); % Fit Gaussian to data points using MSE
mse4 = cost(p2,a)
me2 = p2(1); % Mean estimated as obtained from the fitting
ve2 = p2(2); % Variance estimated as obtained from the fitting
fxx2 = 1/sqrt(ve2*2*pi)*exp(-(i-me2).^2/2/ve2);

**Gaussian fitting mean Squared error**

function mse = cost(x,a)
% Mean squared error evaluation
% x = Gaussian parameters
% a = abscissa points; ordinate points
% Retrieve measurements
xp = a(1,:); % Abscissa of the measurements
fxp = a(2,:); % Ordinate of the measurements
% Retrieve Gaussian parameters
m = x(1); % Mean
v = x(2); % Variance
% Calculations of the Mean squared error of the fit
fx = 1/sqrt(v*2*pi)*exp(-(xp-m).^2/2/v);
e = fx - fxp;
mse = sum(e.^2);
fx = abs(a*x);
Appendix C

C.1 Program module 1 (CCDdriver)

This program combines and synchronises the different program modules.

```vhdl
-- File: d:\active_hdl_designs\ccddriver\SRC\ccddriver.VHD
-- created by Design Wizard: 04/03/04 05:18:58

--{ Section below this comment is automatically maintained
-- and may be overwritten
--{entity {ccddriver} architecture {ccddriver}}

library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.STD_LOGIC_ARITH.ALL;
use IEEE.STD_LOGIC_UNSIGNED.ALL;

entity driver is
  port ( inclk   : IN STD_LOGIC;
         datain_1, datain_2 : IN  STD_LOGIC_VECTOR(12 downto 0);
         dataout_1,dataout_2 : OUT STD_LOGIC_VECTOR(12 downto 0);
         cntrog_prb  : OUT STD_LOGIC_VECTOR(12 downto 0);
         tmpc_prb1,tmpcs_prb1,tmpd_prb1  : OUT STD_LOGIC_VECTOR(12 downto 0);
         tmpc_prb2,tmpcs_prb2,tmpd_prb2  : OUT STD_LOGIC_VECTOR(12 downto 0);
         encode_1,
         encode_2 : OUT STD_LOGIC;
         RS, ROG_out, Q1, Q2 : OUT STD_LOGIC
       );
end driver;

architecture ccddriver of driver is

COMPONENT clk
  PORT(
    inclk0 : IN STD_LOGIC := '0';
    locked : OUT STD_LOGIC ;
    c0    : OUT STD_LOGIC
  );
END COMPONENT;

COMPONENT counter
  PORT(
    clkset : IN STD_LOGIC := '0';
    locked : IN STD_LOGIC := '1';
    cntclk : OUT STD_LOGIC_VECTOR (5 downto 0);  -- counter output clk divider
    cntrog : OUT STD_LOGIC_VECTOR (12 downto 0)
  );
END COMPONENT;

COMPONENT arithmetic
  PORT(
  );
END COMPONENT;
```

94
BEGIN

status : process(clks,cnt1,ENCCDCLK,countrog,encoding)
begin
if clks'event and clks = '1' then

if cnt1 = "000000" and ENCCDCLK = '0' then --cycle of 2MHz Period.
    Q1 <= '1';
    Q2 <= '0';
    RS <= '1';
    encoding <= '0';
else if cnt1 = "000000" and ENCCDCLK = '1' then --default values when ROG = high.
    Q1 <= '1';
    Q2 <= '0';
    RS <= '1';
    --10
else if cnt1 = "001010" and ENCCDCLK = '0' then -- (10) reset RS while Q1 "high"
    RS <= '0';
    --20
else if cnt1 = "010100" and ENCCDCLK = '0' then -- (20)cnt half period
    Q1 <= '0';
    Q2 <= '1';
    --26
else if cnt1 = "011010" then -- captures data and allowing aperture delay tA
    datain_capt_1 <= datain_1;
    datain_capt_2 <= datain_2;
    --25
    --69
    --2777
else if cnt1 = "011001" and ENCCDCLK = '0' and countrog >= "000001000101" and countrog <= "101011011001" then
    encoding <= '1';
end if; end if; end if; end if; end if;
end if;
encode_1 <= encoding;
encode_2 <= encoding;

end process;

ROGate : process(countrog, clks, ROG)
begin
  -- if countrog >= "000000000000" and countrog <= "000000000100" then
  ENCCDCLK <= '1';
  else
    ENCCDCLK <= '0';
  end if;
  --
  if countrog > "000000000000" and countrog <= "000000000011" then
         -- Read out Gate set and reset.
    TempROG := '1';
  else
    TempROG := '0';
  end if;
  ROG<= (countrog(0) or countrog(1))
  and not
    (countrog(2) or countrog(3) or
     countrog(4) or countrog(5) or
     countrog(6) or countrog(7) or
     countrog(8) or countrog(9) or
     countrog(10) or countrog(11) or
     countrog(12))
  );
  ROG_out<=ROG;
  -- ROG <= TempROG;
  -- ROG <= TempROG;
end process;

process(clks)
begin
  if rising_edge(clks) then
    cntrog_prb <= countrog;
  end if;
end process;

counter_inst : counter PORT MAP (;
  clkset => clks,
  locked => locked,
  cntclk => cnt1, -- counter output clk divider
  cntrog => countrog
);
clock_inst : clk PORT MAP (  
  inclk0  => inclk,  
  locked  => locked,  
  c0      => clks  
);

arithmetic_inst_1 : arithmetic PORT MAP (  
  clkset       => clks,  
  encode_in    => encoding,  
  cntROG       => countrog,  
  datain_capt  => datain_capt_1,  
  dataout      => dataout_1,  
  tmpc_prb     => tmpc_prb1,  
  tmpcs_prb    => tmpcs_prb1,  
  tmpd_prb     => tmpd_prb1,  
  ROG_in       => ROG  
);

arithmetic_inst_2 : arithmetic PORT MAP (  
  clkset       => clks,  
  encode_in    => encoding,  
  cntROG       => countrog,  
  datain_capt  => datain_capt_2,  
  dataout      => dataout_2,  
  tmpc_prb     => tmpc_prb2,  
  tmpcs_prb    => tmpcs_prb2,  
  tmpd_prb     => tmpd_prb2,  
  ROG_in       => ROG  
);

end ccddriver;
C.2 Program module 2 (CLK)

This is the FPGA clock, which generates a reliable clock to drive the internal FPGA circuits generated by the program.

-- megafuntion wizard: %ALTPLL%
-- GENERATION: STANDARD
-- VERSION: WM1.0
-- MODULE: altpll

--==============================================================================
-- File Name: clk.vhd
-- Megafuntion Name(s):
--    altpll
--==============================================================================
-- THIS IS A WIZARD-GENERATED FILE. DO NOT EDIT THIS FILE!
--==============================================================================

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--party's intellectual property, are provided herein.

LIBRARY ieee;
USE ieee.std_logic_1164.all;

LIBRARY altera_mf;
USE altera_mf.altera_mf_components.all;

ENTITY clk IS
  PORT
    (   inclk0 : IN STD_LOGIC := '0';
      c0      : OUT STD_LOGIC ;
      locked  : OUT STD_LOGIC
    );
ARCHITECTURE SYN OF clk IS

SIGNAL sub_wire0 : STD_LOGIC_VECTOR (5 DOWNTO 0);
SIGNAL sub_wire1 : STD_LOGIC;
SIGNAL sub_wire2 : STD_LOGIC;
SIGNAL sub_wire3_bv : BIT_VECTOR (0 DOWNTO 0);
SIGNAL sub_wire3 : STD_LOGIC_VECTOR (0 DOWNTO 0);
SIGNAL sub_wire4 : STD_LOGIC_VECTOR (5 DOWNTO 0);
SIGNAL sub_wire5_bv : BIT_VECTOR (0 DOWNTO 0);
SIGNAL sub_wire5 : STD_LOGIC_VECTOR (0 DOWNTO 0);
SIGNAL sub_wire6 : STD_LOGIC;
SIGNAL sub_wire7 : STD_LOGIC_VECTOR (1 DOWNTO 0);
SIGNAL sub_wire8 : STD_LOGIC_VECTOR (3 DOWNTO 0);

COMPONENT altpll
GENERIC (  
  bandwidth_type : STRING;
  clk0_duty_cycle : NATURAL;
  lpm_type : STRING;
  clk0_multiply_by : NATURAL;
  lock_low : NATURAL;
  invalid_lock_multiplier : NATURAL;
  inclk0_input_frequency : NATURAL;
  gate_lock_signal : STRING;
  clk0_divide_by : NATURAL;
  pll_type : STRING;
  valid_lock_multiplier : NATURAL;
  clk0_time_delay : STRING;
  spread_frequency : NATURAL;
  intended_device_family : STRING;
  operation_mode : STRING;
  lock_high : NATURAL;
  compensate_clock : STRING;
  clk0_phase_shift : STRING
);
PORT (  
  clkena : IN STD_LOGIC_VECTOR (5 DOWNTO 0);
  inclk : IN STD_LOGIC_VECTOR (1 DOWNTO 0);
  extclkena : IN STD_LOGIC_VECTOR (3 DOWNTO 0);
  locked : OUT STD_LOGIC ;
  clk : OUT STD_LOGIC_VECTOR (5 DOWNTO 0)
);
END COMPONENT;

BEGIN
  sub_wire3_bv(0 DOWNTO 0) <= "0";
  sub_wire3 <= To_stdlogicvector(sub_wire3_bv);
  sub_wire5_bv(0 DOWNTO 0) <= "0";
  sub_wire5 <= NOT(To_stdlogicvector(sub_wire5_bv));
  sub_wire1 <= sub_wire0(0);
  c0 <= sub_wire1;
  locked <= sub_wire2;

END clk;
sub_wire4 <= sub_wire3(0 DOWNTO 0) & sub_wire3(0 DOWNTO 0) & sub_wire3(0 DOWNTO 0) & sub_wire3(0 DOWNTO 0) & sub_wire5(0 DOWNTO 0);
sub_wire6 <= inclk;
sub_wire7 <= sub_wire3(0 DOWNTO 0) & sub_wire6;
sub_wire8 <= sub_wire3(0 DOWNTO 0) & sub_wire3(0 DOWNTO 0) & sub_wire3(0 DOWNTO 0) & sub_wire3(0 DOWNTO 0) & sub_wire5(0 DOWNTO 0);

altpll_component : altpll
GENERIC MAP (  
  bandwidth_type => "AUTO",  
  clk0_duty_cycle => 50,  
  lpm_type => "altpll",  
  clk0_multiply_by => 1,  
  lock_low => 5,  
  invalid_lock_multiplier => 5,  
  inclk0_input_frequency => 12500,  
  gate_lock_signal => "NO",  
  clk0_divide_by => 1,  
  pll_type => "AUTO",  
  valid_lock_multiplier => 1,  
  clk0_time_delay => "0",  
  spread_frequency => 0,  
  intended_device_family => "Stratix",  
  operation_mode => "NORMAL",  
  lock_high => 1,  
  compensate_clock => "CLK0",  
  clk0_phase_shift => "0"
)
PORT MAP (  
  clkena => sub_wire4,  
  inclk => sub_wire7,  
  extclkena => sub_wire8,  
  clk => sub_wire0,  
  locked => sub_wire2
)

END SYN;
C.3 Program module 3 (counter)

This program is basically implementing clock delays referenced from the ALTPPLL clock. It is comprised of counters used to shape the waveform for the drivers and for signal timing.

LIBRARY ieee;
USE ieee.std_logic_1164.all;
use IEEE.STD_LOGIC_ARITH.ALL;
use IEEE.STD_LOGIC_UNSIGNED.ALL;

ENTITY counter IS
  PORT
     (clkset  : IN STD_LOGIC  := '0';
      locked  : IN STD_LOGIC := '1';
      cntclk  : OUT STD_LOGIC_VECTOR (5 downto 0); -- counter output clk divider
      cntrog  : OUT STD_LOGIC_VECTOR (12 downto 0);-- counter output ROG
     );
END counter;

ARCHITECTURE SYN OF counter IS
signal cnt  : STD_LOGIC_VECTOR (5 downto 0); -- counter output
signal cnt_rog : STD_LOGIC_VECTOR (12 downto 0);
begin
  cnt_slow:process(clkset,locked,cnt,cnt_rog)
    begin
      if locked='0' then
        cnt<=(others=>'0');
      elsif rising_edge(clkset) then
        if cnt = "100111" then  --counter  = 0 to 39;
          cnt <= (others =>'0' );
        else
          cnt <= cnt + '1';
        end if;
      end if;
      cntclk <= cnt;
      cntrog <= cnt_rog;
    end process cnt_slow;
  cnt_high:process(clkset,cnt,locked)
    variable tmp: std_logic_vector(12 downto 0):="0000000000000";
    begin
      if locked='0' then
        tmp:=(others=>0');
      else
        if rising_edge(clkset) then
          if cnt = "000000" then -- slower counter
            tmp:="000000000000000000";
          else
            tmp:=(others=>0');
          end if;
        end if;
      end if;
      cntclk <= tmp;
      cntrog <= cnt_rog;
    end process cnt_high;
end SYN;
if tmp = "101011011100" then --counter = 0 to 2780;
    tmp := (others =>'0' );
    else
        tmp := tmp + '1';
        end if;
    end if;
end if;
end if;
end if;
cnt_rog<=tmp;
end process cnt_high;

dend SYN;
C.4 Program module 4 (arithmetic)

This program does all the arithmetic operations.

-- File: d:\active_hdl_designs\ccdarith\SRC\ccdarith.VHD
-- created by Design Wizard: 04/07/04 19:58:16
--{{ Section below this comment is automatically maintained
-- and may be overwritten
--{entity {ccdarith} architecture {ccdarith}}
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.STD_LOGIC_ARITH.ALL;
use IEEE.STD_LOGIC_UNSIGNED.ALL;

entity arithmetic is
port (
    clkset    : IN std_logic;
    datain_capt   : IN STD_LOGIC_VECTOR(12 downto 0);
    cntROG    : IN STD_LOGIC_VECTOR(12 downto 0);
    dataout    : OUT STD_LOGIC_VECTOR(12 downto 0);
    tmpc_prb    : OUT STD_LOGIC_VECTOR(12 downto 0);
    tmpcs_prb,tmpd_prb    : OUT STD_LOGIC_VECTOR(12 downto 0);
    encode_in   : IN STD_LOGIC;
    ROG_in    : IN STD_LOGIC;
);
end arithmetic;

architecture cccdarith of arithmetic is
signal tmpc  : STD_LOGIC_VECTOR(12 downto 0); --temporal counter storage, corresponding to datain
Signal tmpd  : STD_LOGIC_VECTOR(12 downto 0); --2047temporal datain storage from th ADC
signal tmpcs : STD_LOGIC_VECTOR(12 downto 0); --2047temporal datain storage from th ADC
signal encod_flag : STD_LOGIC;
begin
process(ROG_in,encode_in,cntROG,datain_capt,encod_flag,tmpcs,tmpc,tmpd)
begin
    if rising_edge(ROG_in) and ROG_in = '1' then
        if tmpc <= (tmpcs + "0000000000001") and tmpc >= (tmpcs-"0000000000001") then
            dataout <= tmpcs - "0000001001111";--79
            encod_flag <= '1';
        else
            dataout  <= tmpc - "0000001001111"; --79 remebor to subtarct 79 from tmpc in the end.
            tmpcs <= tmpc;
            encod_flag <= '1';
        end if;
    end if;
    if encod_flag = '1' and ROG_in = '0' and encode_in = '0' then
        encod_flag <= '0';
    end if;
    tmpcs_prb <= tmpcs;
end process;
"} End of automatically maintained section
architecture cccdarith of arithmetic is

signal tmpcs : STD_LOGIC_VECTOR(12 downto 0); --2047temporal datain storage from th ADC
signal encod_flag : STD_LOGIC;
begin
    process(ROG_in,encode_in,cntROG,datain_capt,encod_flag,tmpcs,tmpc,tmpd)
    begin
        if rising_edge(ROG_in) and ROG_in = '1' then
            if tmpcs <= (tmpcs + "0000000000001") and tmpcs >= (tmpcs-"0000000000001") then
                dataout <= tmpcs - "0000001001111";--79
                encod_flag <= '1';
            else
                dataout  <= tmpcs - "0000001001111"; --79 remebor to subtarct 79 from tmpcs in the end.
            end if;
            tmpcs <= tmpcs;
            encod_flag <= '1';
        end if;
        if encod_flag = '1' and ROG_in = '0' and encode_in = '0' then
            encod_flag <= '0';
        end if;
        tmpcs_prb <= tmpcs;
    end process;
end arithmetic;
process (encode_in,cntROG,datain_capt,tmpd,tmpc,clkset)
begin
    if rising_edge(clkset) then
        if encode_in = '1' and cntROG > "0000001001111" and datain_capt <= tmpd then --
            tmpd <= datain_capt;--temp data store that particular value as new thresh-hold.
            tmpc <= cntROG;  --temp counter store the counter value, it represents the position
        else
            tmpc<=tmpc;
            if encod_flag = '1' then
                tmpd <= "0011111111111";  --2047
            else
                tmpd <=tmpd;
            end if;
        end if;
    end if;
    tmpc_prb  <= tmpc;
    tmpd_prb  <= tmpd;
end process;
end ccdarith;
C.5 EDK C Program for automated data serial (RS232) acquisition.

// Located in: microblaze_0/include/xparameters.h
#include "xparameters.h"
#include "xgpio.h"
#include <stdio.h>
#include <stdlib.h>
#include "xutil.h"
#define DATAMASK 0x00001fff
#define ROGMASK 0x00008000

//====================================================
int main (void) {

int i1,i2,ROG,IR=0,ID=0,data,r;

/*
 * MemoryTest routine will not be run for the memory at
 * 0x00000000 (dlmb_cntlr)
 * because it is being used to hold a part of this application program
 */

i1=XGpio_mReadReg(XPAR_OPB_GPIO_0_BASEADDR,0);
ROG = i1&ROGMASK; // 32768
data = i1&DATAMASK;

while (ROG == 0)
{
    NULL; //to display nothing
    break;
}

while (ROG == 32768)
{
    r++; xil_printf("data(%04d) = %04d \r\n",r,data); break;
}

if (r == 1000)
{
    r=0;
    xil_printf("\r\n\r\n---- DATA ACQUISITION START ----\r\n\nDATA INDEX MEASUREMENT DATA \r\n" );
    return main();
}

return main(); //returns back to the begining of the program
}
Appendix D

D.1 Data sheets

Sony

ILX535K

5300 pixel × 3 line CCD Linear Sensor (Color)

Description
The ILX535K is a reduced type CCD linear sensor developed for color image scanners. The distance between lines is only 4 line (32μm). This sensor reads A4-size documents at a density of 600 DPI.

Features
• Number of effective pixels: 15900 pixels
  (5300 pixels × 3)
• Pixel size: 8μm × 8μm (8μm pitch)
• Distance between line: 32μm (4 Lines)
• Number of output: 3 (R, G, B)
• Single-sided readout
• Clamp circuit on-chip
• Ultra high sensitivity/ Ultra low lag
• Single 12V power supply
• Maximum data rate: 9MHz (3MHz × 3)
• Input Clock Pulse: CMOS 5V drive
• Package: 22 pin Plastic-DIP (400 mil)

Absolute Maximum Ratings
• Supply voltage Vcc 15 V
• Operating temperature -10 to +55 ºC
• Storage temperature -30 to +80 ºC

Pin Configuration (Top View)

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Example of Representative Characteristics (Vcc = 12V, Ta = 25°C)

- Spectral sensitivity characteristics
- Dark signal output temperature characteristics
- Integration time output voltage characteristics
- Offset level vs. Vcc characteristics
- Offset level vs. temperature characteristics
The Stratix™ EP1S25 DSP development board is included with the DSP Development Kit, Stratix Edition (ordering code: DSP-BOARD/SP25). This board is a powerful development platform for digital signal processing (DSP) designs, and features the Stratix EP1S25 device in the fastest speed grade (-5) 780-pin package.

**Components**

- Analog I/O
  - Two 12-bit 125-MHz A/D converters
  - Two 14-bit 165-MHz D/A converters
  - Single-ended or differential inputs, and single-ended outputs
- Memory subsystem
  - 2 MBytes of 7.5-ns synchronous SRAM configured as two independent 36-bit buses
  - 32 Mbits of flash memory
- Configuration options
  - On-board configuration via the 32 Mbits of flash memory, plus the Altera® EPM7064 device
  - Download configuration data using ByteBlasterMV™ download cables
- Dual seven-segment display
- One 8-pin dipswitch
- Three user-definable pushbutton switches
- One 9-pin PS-232 connector
- Two user-definable LEDs
- On-board 80-MHz oscillator
- Single 5-V DC power supply (adapter included)

**Debugging Interfaces**

- Two NI Aurora-type connectors for Hewlett Packard (HP) logic analyzers
- Several 0.1-inch headers

**Expansion Interfaces**

- Two connectors for Analog Devices A/D converter daughter cards
- Connector for Texas Instruments EVM Evaluation Module (TI-EVM) daughter cards
Appendix E

E.1 Experimental set-up pictures

Figure E-1: Test with a simple experimental set-up.

Figure E-2: Two dimensional tests model.

Figure E-3: Test on a stabilised optical table with micrometre.

Figure E-4: CCD frame response.