DEVELOPMENT OF AN IMAGE ROTARY ENCODER FOR MOTION CONTROL

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ISMAYUZRI BIN ISHAK

Thesis submitted in fulfillment of the requirements
for the award of the degree of
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APRIL 2013

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Engineering in Manufacturing.

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ABSTRACT

A rotary encoder reads rotational motion (angular position and speed) and converts the motion into electrical signals. It involves two components: a designed coded-disc to represents rotational information and a sensor to convert the coded information into electrical signals. A conventional rotary encoder uses three major elements, a pattern code disc, a light source and a photo-detector. Factors affecting rotary encoder are mechanical component alignments, resolution enhancement, size reduction, additional processing electronics and the working environment. Depending on the design of the coded-disc and the signal interpolation, a rotary encoder can function as an absolute or incremental encoder. An absolute encoder can determine the angular position without the need to have a reference position. On the other hand, an incremental encoder requires a reference position in order to determine the angular position. In operations, when an incremental encoder is started, the system has to move to the home position in order to set a reference point. An absolute encoder does not require home operations because it knows exactly the current angular position. As such, an incremental encoder requires an additional power supply when the system is turn-off so that it can "memorize" the current position. An absolute encoder is more expensive and the angular position range is limited by the disc size. Many researchers proposed and implemented different alternatives to absolute encoder. One technique is using an image rotary encoder. Current trends in digital image processing techniques have been applied widely into various applications. Some of the applications emerge as a sensing device with the assist of digital image processing techniques. Therefore, the research objective is to develop an image rotary encoder based on image texture before converting it into speed and motion data. The image texture is captured from a specially-designed texture of rotating disc using a digital image sensor. The proposed image rotary encoder is based on pixel changes by motion of rotating disc. The captured images are then converted into motion data by an image processing algorithm. The output signal is a binary position code which is similar to the conventional absolute rotary encoder. Performance of the image rotary encoder is validated by comparing the speed and position with the conventional rotary encoder. Experimental results indicate that the speed and position measured by the developed image rotary encoder are directly proportional to those measured using the conventional rotary encoder. Experiments also confirmed that the developed image rotary encoder can be utilized as a feedback device to a DC motor PID position control. Therefore, the developed image rotary encoder successfully functions as an absolute rotary encoder.

ABSTRAK

Pengekod putaran membaca gerakan putaran (kedudukan sudut dan kelajuan) dan menukarkan gerakan menjadi isyarat elektrik. Ia melibatkan dua komponen: cakera berkod yang direka untuk mewakili maklumat putaran dan alat pengesan untuk menukar maklumat berkod kepada isyarat elektrik. Pengekod putaran konvensional menggunakan tiga elemen utama, cakera corak berkod, sumber cahaya dan pengesan cahaya. Faktor-faktor yang memberi kesan kepada pengekod putaran adalah penjajaran komponen mekanikal, peningkatan resolusi, pengurangan saiz, tambahan pemprosesan elektronik dan persekitaran kerja. Bergantung kepada reka bentuk cakera berkod-dan interpolasi isyarat, pengekod putaran boleh berfungsi sebagai pengekod mutlak atau pengekod tokokan. Pengekod mutlak boleh menentukan kedudukan sudut tanpa memerlukan kedudukan rujukan. Sebaliknya, pengekod tokokan memerlukan kedudukan rujukan untuk menentukan kedudukan sudut. Dalam operasi, apabila pengekod tokokan bermula, sistem ini perlu untuk bergerak ke kedudukan penetapan rumah bagi membolehkan menetapkan titik rujukan. Pengekod mutlak tidak memerlukan operasi penetapan rumah kerana ia tahu kedudukan sudut semasa. Oleh itu, pengekod tokokan memerlukan bekalan kuasa tambahan apabila sistem dimatikan supaya ia boleh "mengingati" kedudukan semasa. Pengekod mutlak adalah lebih mahal dan julat kedudukan sudut dihadkan oleh saiz cakera. Ramai penyelidik yang mencadangkan dan melaksanakan alternatif yang berbeza untuk pengekod mutlak. Salah satu teknik menggunakan pengekod imej putaran. Perkembangan terkini di dalam teknik pemprosesan imej digital telah banyak digunakan di dalam pelbagai aplikasi. Sesetengah aplikasi tersebut muncul sebagai alat pengukuran dengan bantuan teknik pemprosesan imej digital. Oleh itu, objektif kajian adalah untuk membangunkan pengekod imej sebagai isyarat menerima yang berkesan berdasarkan tekstur imej sebelum menukarkan ia kepada data kelajuan dan pergerakan. Tekstur imej diambil daripada tekstur yang direka khas diatas cakera putaran menggunakan alat pengesan imej digital. Isyarat berkesan yang dicadangkan berdasarkan perubahan piksel dengan memutar cakera. Isyarat ini kemudiannya ditukar ke dalam data gerakan oleh algoritma pemprosesan imej. Isyarat yang dikeluarkan adalah kedudukan kod binari yang serupa dengan pengekod konvensional putaran mutlak. Prestasi pengekod putaran imej disahkan dengan membandingkan kelajuan dan kedudukan dengan pengekod putaran konvensional. Keputusan eksperimen menunjukkan bahawa kelajuan dan kedudukan yang diukur oleh pengekod putaran imej yang dibangunkan adalah berkadar terus dengan pengekod putaran konvensional. Eksperimen juga mengesahkan bahawa pengekod putaran imej yang dibangunkan boleh digunakan sebagai alat maklum balas kepada kedudukan kawalan PID DC motor. Oleh itu, pengekod putaran imej yang dibangunkan berjaya berfungsi sebagai pengekod putaran mutlak.

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LIST OF SYMBOLS

$m_{p,q}$	Contour moment
θ	Angle
$\omega_{\max}$	Maximum speed (RPM)
T_{pt}	Processing time
K_p	Proportional gain constant
K_i	Integral gain constant
K_d	Derivative gain constant
K_{pu}	Critical gain constant
T_r	Rise time
T_p	Peak time
T_s	Settling time
T_u	Period of time for K_{pu}
r	Coefficient of correlation

LIST OF ABBREVIATIONS

ADC	Analog to Digital Converter
BPC	Binary Position Code
CAD	Computer Aided Design
CCD	Charged Coupled Device
CMOS	Complementary Metal Oxide Semiconductor
COG	Centre of Gravity
CTE	Coefficient of Thermal Expansion
DAC	Digital to Analog Converter
DC	Direct Current
DSP	Digital Signal Processing
EPP	Enhanced Parallel Port
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LED	Light Emitting Diode
NI	National Instruments
OS	Operating System
PID	Proportional, Integral and Derivative
RPM	Revolution per Minute
USB	Universal Serial Bus
ZN	Ziegler-Nichols

CHAPTER 1

INTRODUCTION

1.1 RESEARCH MOTIVATION

Rotary encoders are transducers that convert angular motion of a rotating object to electrical signals. They are used to provide the angular position of a rotating object and its rate of changes. At this moment, several rotary encoder designs exists, which includes the direct contact (or brush-type) and the magnetic rotary encoders (Sclater and Chironis, 2007). Generally, the optical rotary encoders are widely used because they possess higher speed, higher precision and lower cost (Oka et al., 2009). These simple and small units are made from a patterned code disk, a light source and a photodetector.

Conventional method have been used the optical rotary encoder as the motion control system. In particular, they are used in mechanical systems as an inexpensive and reliable way to measure the rotation of moving objects. For example, they are used in the digital cameras to detect the position of lenses (Igaki and Atsuta, 2008). Although the optical rotary encoder is used in many applications, their performance is less satisfactory (Wang et al., 2008). In fact, there is a continuing trend for improving the precision and the resolution of the optical rotary encoder (Villaret, 2008).

Current trends in digital image processing techniques have been applied widely into various applications. Some of the applications emerge as a sensing device with the assist of digital image processing techniques (Minoni *et. al* (2006), Tresanchez *et. al* (2009), Tresanchez *et. al* (2010a), Tresanchez *et. al* (2010b), Zhu and Yu (2011) Douglas *et. al* (1999)). Due to this trend, implementation of digital image processing techniques to image rotary encoder as a feedback device can be applied. This is the research motivation.

1.2 RESEARCH PROBLEM STATEMENT

One of the measurement device used in a high precision motion is a rotary encoder. It is widely used in machine tools and robotics as a feedback device to the actuator under a closed loop control system. In fact, it is an essential tool in a modern manufacturing application.

A rotary encoder "reads" rotational motion (angular position and speed) and converts the motion into electrical signals. It involves two components: a designed coded-disc to represents rotational information and a sensor to convert the coded information into electrical signals.

A conventional rotary encoder uses three major elements, a pattern code disc, a light source and a photo-detector. All elements contribute to the performance of the conventional rotary encoder. There are five factors affecting rotary encoder performance which are (1) mechanical alignments of components in the rotary encoders, (2) resolution enhancement of the rotary encoders, (3) size reduction of the rotary encoders, (4) additional electronics in the rotary encoders and (5) working environment of the encoders.

Firstly, mechanical alignments refer to the eccentricity between the code disc, the light source and the photo-detector. Misalignment often occurs during the assembly process (Musha et al. (2008), Yoshioka (2009), Hasegawa (2009)). Secondly, the resolution of the rotary encoder depends on the number of slit pattern in the code disc. In order to increase the number of slits, distance between the slits has to decrease (Wei, 2008). However, this is limited by the size and fabrication process. Furthermore, decreasing the slits distance increases the chances of creating irregularity that will introduce noise in the output signal (Villaret, 2008). Thirdly, to improve the performance of the encoder, it can be done by reducing the rotary encoder sizes. Nowadays, some of the rotary encoder application needs smaller sizes of rotary encoder in order to integrate with smaller size devices. Fourthly, with assists of additional electronic, the resolution of an encoder can be increased by signal interpolation. Additional electronics will contribute to increasing in production cost and cause a delay in signal processing. Finally, working environment and unwanted reflection light can contribute to noise and signal interference to the rotary encoder system.

Depending on the design of the code disc and the signal interpolation, a rotary encoder can function as an absolute or incremental encoder. An absolute encoder can determine the angular position without the need to have a reference position. On the other hand, an incremental encoder requires a reference position in order to determine the angular position. In operations, when an incremental encoder is started, the system has to move to the home position in order to set a reference point. An absolute encoder does not require home operations because it knows exactly the angular position when started. As such, an incremental encoder requires an additional power supply when the system is turn-off so that it can "memorize" the current position.

An absolute encoder is more expensive and the angular position range is limited by the disc size. There are researchers proposed and implemented different alternatives to absolute encoder. One technique is by using an image rotary encoder. Therefore, the research objective is to develop an image rotary encoder based on image texture before converting it into speed and motion data. The image texture is captured from a specially-designed texture of rotating disc using a digital image sensor. The proposed image rotary encoder is based on pixel changes by motion of rotating disc. The captured images are then converted into motion data by an image processing algorithm. The output signal is an absolute position similar to conventional absolute rotary encoder.

1.3 RESEARCH OBJECTIVES

There are three objectives which are:

1. To develop a prototype of a new rotary absolute encoder using image as feedback information.
2. To develop an algorithm to process the image feedback as position data.

3. To verify the performance of the developed system under position control.

1.4 RESEARCH SCOPE

In order to achieve the research objectives, two research scopes have been identified:

1. The developed image rotary encoder is an absolute rotary encoder with 10 bits output.
2. Physical experiment is designed and conducted to validate the performance of the developed image rotary encoder for position control only. Speed control is not part of this research.

1.5 RESEARCH METHODOLOGY

This research is carried out through three main stages, which are:

Firstly, literature reviews and background knowledge of image rotary encoder are conducted. This review is to know the principles of rotary encoder, the classification and types between rotary encoder, design and application of rotary encoders, factors effecting optical rotary encoder performance, previous research on image rotary encoder as well as their limitation and resolution improvement.

Secondly, a new method is proposed in order to develop an image rotary encoder. The proposed method, which is based on the image processing, is applied to develop as a position control device.

Lastly, experiments applying developed image rotary encoder for position control were conducted. The developed image rotary performance is characterised and validated with conventional optical rotary encoder. Experiments are conducted by implementing the developed image rotary encoder in a DC motor PID position control.

1.6 THESIS ORGANIZATION

This thesis is organized as follows:

Chapter 2: Literature Review and Background Knowledge Rotary Encoders

This chapter describes basics of control system, motor servo systems, rotary encoder from background knowledge as well as literature review perspectives, optical rotary encoder performance factor, current research on image rotary encoder and improvement on rotary encoder. The types and classification of rotary encoder with emphasis on working principles are presented. Next, types of current rotary encoders are presented. Design and application of rotary encoders are also discussed. Finally, review of current technologies on rotary encoders and resolution improvement based on velocity estimation for rotary encoder are presented in detailed.

Chapter 3: Hardware and Software Design of Image Rotary Encoder

This chapter presents design and methodology to develop image rotary encoder. The design of the system is explained and each system component is described and discussed.

Chapter 4: Experiment and Data Validation of Image Rotary Encoder

This chapter presents the objectives of experiments, experimental setup, experimental results, performance validation and analysis of the develop image rotary encoder.

Lastly in **Chapter 5: Research Conclusion**

This chapter concludes the research and recommendations for future works.

CHAPTER 2

LITERATURE REVIEW AND BACKGROUND KNOWLEDGE OF IMAGE ROTARY ENCODERS

2.1 INTRODUCTION

This chapter presents the review and background knowledge of the image rotary encoders. Firstly, the basics of control system and the motor servo system are presented. Then, the mechanism and the type of rotary encoder are described. Detailed explanations on classification of rotary encoder together with descriptions and differences between the incremental and absolute encoder are presented followed by the factors affecting optical rotary encoder designs as well as the major factors affecting the encoder for higher performance are highlighted. Then, the discussions of previous researches on image rotary encoder and their limitations are discussed. Finally, the velocity estimation techniques are described for resolution improvement of rotary encoder.

In general, an image rotary encoder is a component of a control system. A control system is a combination of machine intelligence and components that work together in order to control a system (Kilian, 2006). A control system generates an output based on a given input, as shown in Figure 2.1.

Figure 2.1: Basic block diagram of a control system

Source: Nise (2004)

The main reasons for implementing a control system is to amplify the system power, to remotely control the system, to easily relate between the system input and output and to reject disturbance on the system.

Another example of a control system is a position control of an antenna system. In order to control the angular position of an antenna, the input is just a low power possibly through angular rotation of a knob, but the control system proportionately amplifies the power to rotate the position of the antenna. Furthermore, through a control system, the position of the antenna can be controlled remotely; the rotation of the knob can be operated further from the antenna. To easily relate between input and output, a control system does not require the physical variables of the input to be similar to the physical variable of the output. In the case on an antenna, the input may be in a form of voltage signal but the output is the angle of rotation, as long as there is a “relationship” between the voltage input and the angular position output. Thus, a convenient signal input can control a desired antenna position. Lastly, a control system can implement disturbance rejection. For instance, the wind forces may cause the antenna to deviate from the desired position. A proper antenna control system is capable of detecting the wind forces and implement compensation to ensure the antenna remains at the desired position.

A control system can be described in two configurations: open loop and closed loop. An open loop control system is a system that responds directly from the input. A block diagram of open loop system is shown in Figure 2.2.

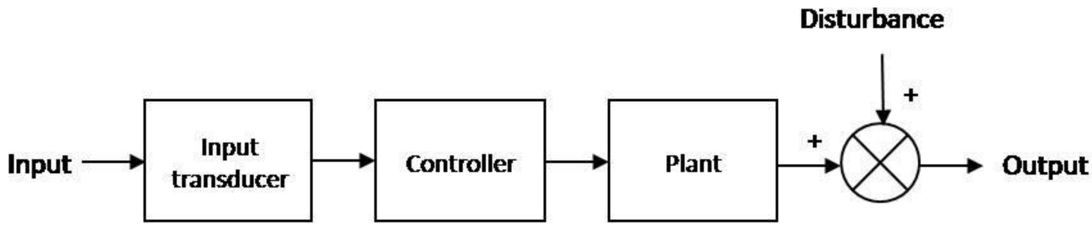


Figure 2.2: An open loop system configuration

When an input is triggered, the input transducer will feed a desired signal to the controller which then drives the plant. For example, when a knob (rotary potentiometer) is turned, proportionate electrical signals representing the desired angle of rotation are sent to the controller. The controller then amplifies the signals and drives the plant. The plant then gives the actual output. Because of the presence of disturbances, the actual output will not achieve the desired output. Examples of disturbances are friction in the system or external loads. An open loop system, due to its configuration, is not able to perform automatic input adjustment. Thus, the desired output can only be achieved through manual control of the input.

For an example in an open loop system is a simple drilling machine. The desired speed of the drilling is set initially by the input. However, when the drill bit touches the work piece, the speed is reduced because the contact forces that occur during the drilling process is a disturbance to the system. Furthermore, the speed of the drilling will vary depends on the work piece material. Different work piece material induces different cutting forces that affect the drilling speed. To achieve the desired drilling speed, the operator has to manually adjust the input signal.

A closed loop system, on the other hand, is a system that has a feedback system and can automatically regulate the desired output. A closed loop system incorporates a sensor attached to the output of the system in order to sense the actual output. Signal from the sensor is then utilized by the controller, so that appropriate adjustment signals can be delivered to the plant.

A block diagram of a closed loop system is shown in Figure 2.3. The output is measured by a sensor or a transducer and feed to the summing junction. The summing junction calculates the difference between the desired input and the actual output. The difference is compensated by the controller by driving the difference to zero.

Although the major function of a feedback system is to achieve the desired target automatically, the design of the controller is also used to “speed up” the response of the system to the desired output while maintaining the stability of the system.

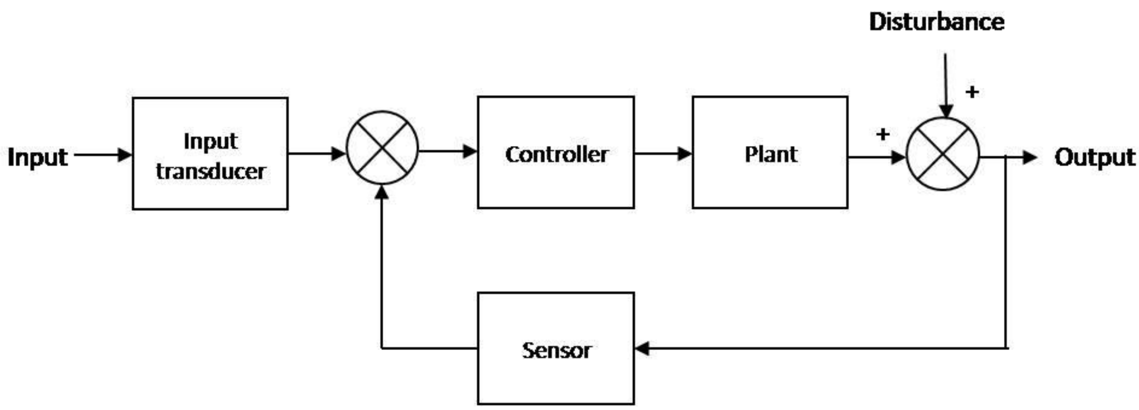


Figure 2.3: A closed loop system configuration

2.2 MOTOR SERVO CONTROL LOOP

A closed loop system is widely used in servo motor applications. Servo motors are widely used in many machines and robotic applications. Servo motor is a mechanism to control the desired motor output based on feedback (Younkin, 2002). It consists of a motor, electronic driver and feedback devices in order to control the velocity, position and torque of a motor. The servo system is designed to response to command changes and accommodate load disturbances.

One of the feedback devices used in servo motor system is an encoder. An encoder, in the servo motor system, is an independent physical device that is coupled to the motor shaft to get the speed and position of the motor. An encoder works as a transducer and provides coded information that is translated as position or speed. There are two types of encoders: linear and rotary encoder. Linear encoder is used as a position and speed transducer in a linear motion whereas rotary encoder is used in rotary motion. The application of linear and rotary encoder is shown in Figure 2.4. In Figure 2.4, a Mitutoyo T-115 linear encoder is attached to the y-axis of the Okamoto Grinding Machine is shown while in Figure 2.5 a rotary encoder attached to FANUC servo motor for FANUC robotic arm is shown.

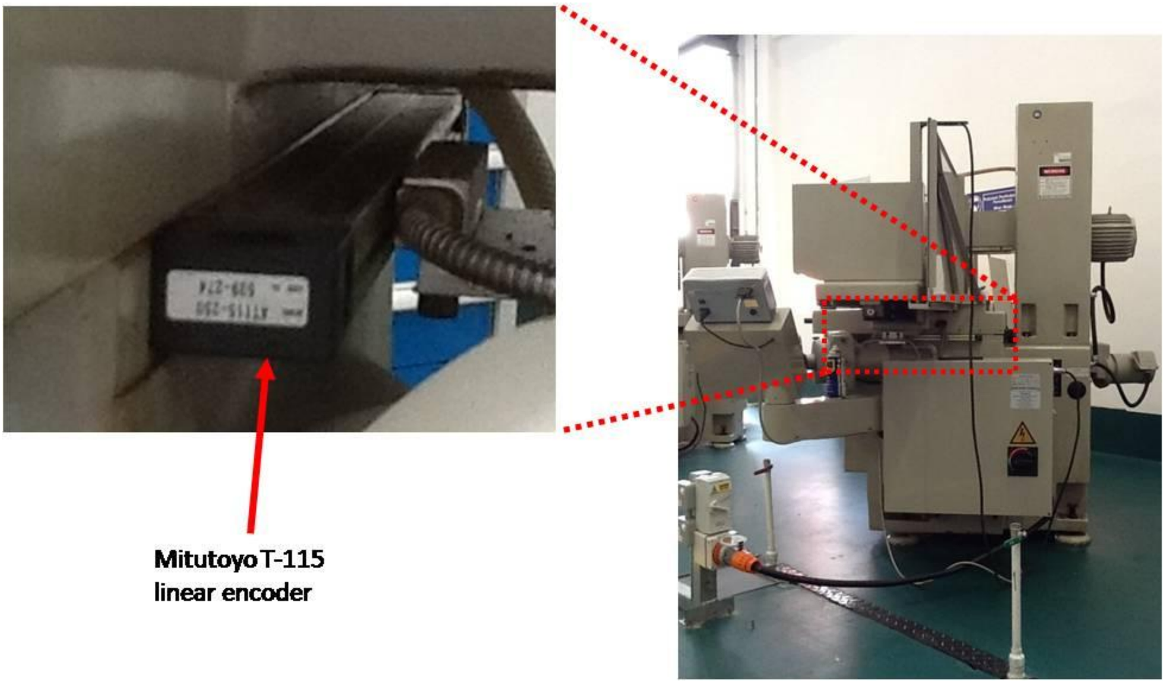


Figure 2.4: Example of a linear encoder attached to the y-axis

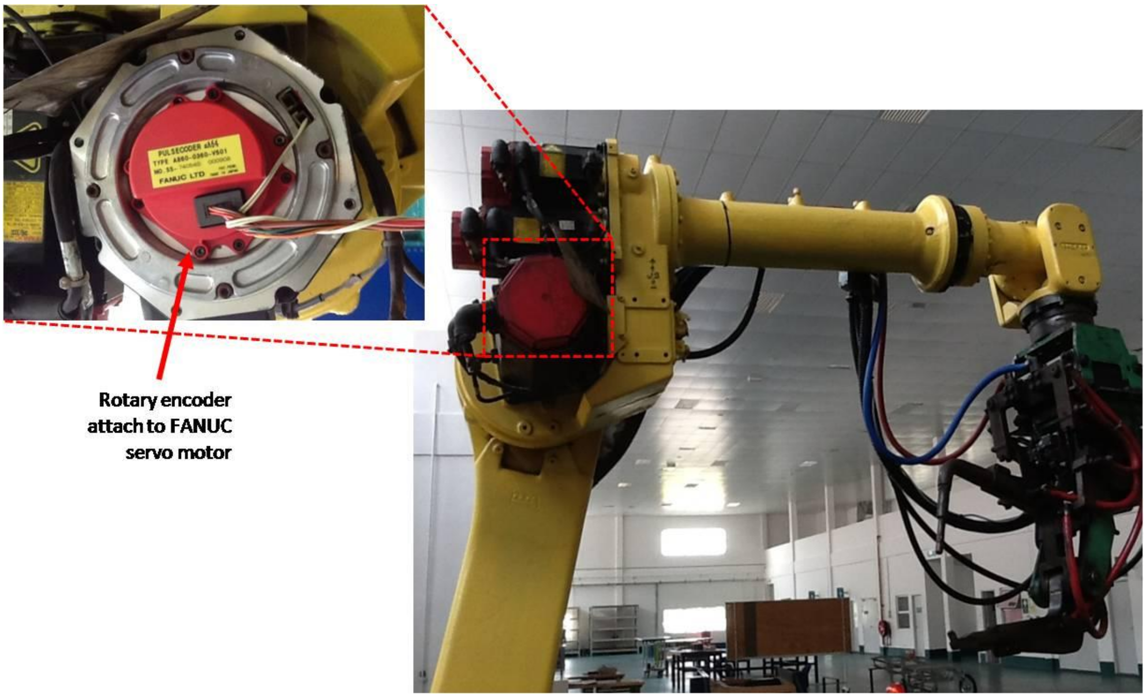


Figure 2.5: Example of a rotary encoder attached to robotic arm servo motor

2.3 TYPES OF ROTARY ENCODERS

The rotary encoders are electromechanical transducers that convert rotary mechanical movement into electrical signals (Sclater and Chironis, 2007). The signals are used to determine the angular position and speed of the rotational movement. Rotary encoder can be grouped into two types: optical rotary encoder and magnetic rotary encoder.

2.3.1 Optical Rotary Encoder

Optical rotary encoder operates by producing electric pulses from the rotational motion of the encoder (Bishop et al., 2002). It uses photo-interrupter as a sensing element. Photo-interrupter comprises of photo-detector, mask and light source. The most typically light source is light emitting diodes (LED). It operates by the interruption of code disc (used masking) between the photo-detector and the LED. The exploded view of an industrial grade optical rotary encoder is shown in Figure 2.6.

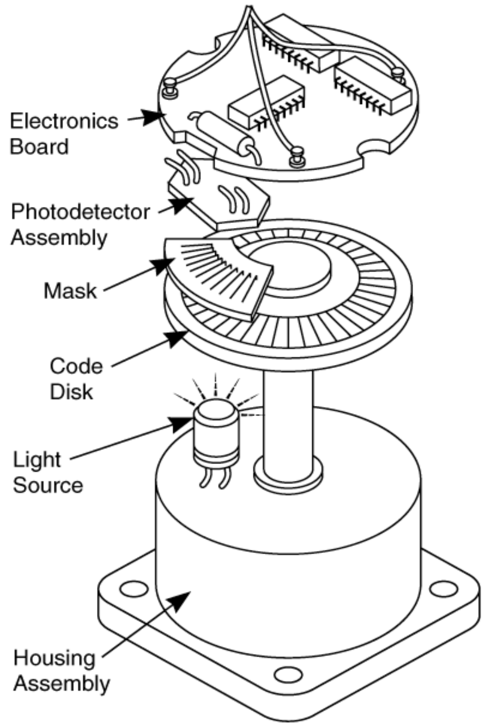


Figure 2.6: Exploded view of an optical rotary encoder showing the stationary mask between the patterned code disc and the photo-detector

Source: Sclater and Chironis (2007)

2.3.2 Magnetic Rotary Encoder

Magnetic rotary encoder is one of the rotational sensors that are widely used because of its robust designed in harsh environment, low cost, simple structure and good adaptability as multifunction device (Wang et al., 2010). Generally, magnetic encoder can be classified into two types: Hall sensor arrays and multi pole drum. Hall sensor arrays use a permanent magnet attached at the rotary shaft with magnetic sensor under it (Burger et al., 2000). Magnetic field is created parallel to the sensor surface by permanent magnet in order to give the output signal. Multi pole drum uses a magneto resistive sensor to detect weak magnetic field to produce sinusoidal output waveforms (Shi et al., 2004).

In this research, a rotary encoder type is studied. As such, in the following sections details information and review about rotary encoder are presented.

2.4 OPTICAL ROTARY ENCODER CLASSIFICATION

The optical rotary encoders, which are also called optical rotary shaft encoders or optical rotary shaft-angle encoders, are electromechanical transducer that is further classified under two classifications: the absolute optical rotary encoders and the incremental optical rotary encoders.

The absolute rotary encoder measures the position based on angular position of the rotational movement to an absolute reference position at any instance by representing it in digital code (Centikunt, 2007). The absolute optical rotary encoders can determine the exact angular position at any moment including during the power-up stage. It provides a binary output to indicate the shaft angle with absolute measurement. This is achieved through a unique pattern on a code disk as shown in Figure 2.7.

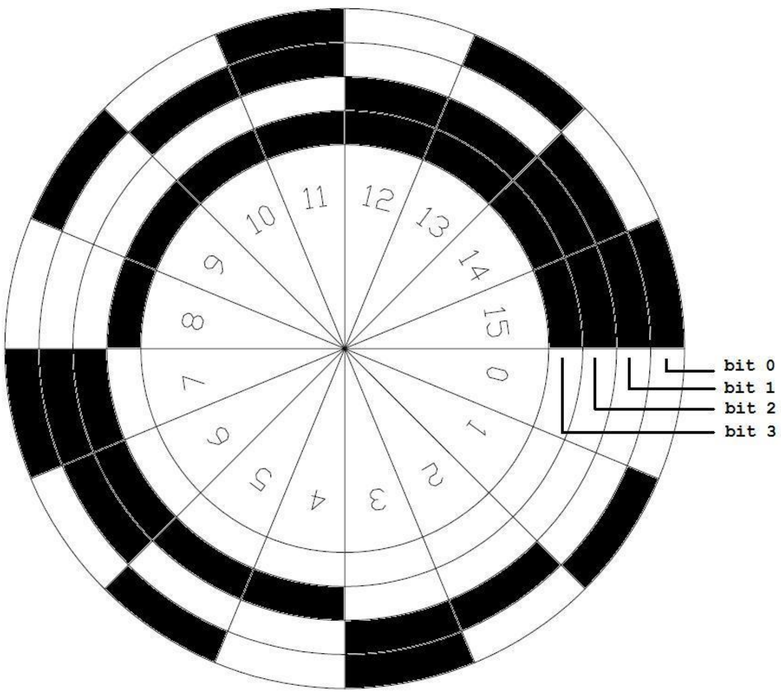


Figure 2.7: Pattern code disc of absolute rotary encoder

In contrast to the absolute rotary encoder, the incremental optical rotary encoders do not have the ability to determine the exact angular position at any instance.

The position of the incremental encoder is based upon a fixed reference position and the current distance from the reference position. The incremental optical rotary encoders are cheaper and require less power than the absolute optical rotary encoders. Furthermore, the resolutions of the incremental optical rotary encoders are comparatively higher (Watanabe, 2008). As the result, the incremental optical rotary encoders are widely used in the current market (Chang and Kress, 2009).

A common type of incremental encoder is a quadrature encoder. It consists of a light emitting diode (LED), a code disc, a mask and a photo-detector. The assembly of an increment rotary encoder is shown in Figure 2.8. All components are assembled parallel to each other whereby the LED illuminates the code disc. The code disc has a pattern or slit that is equally spaced. The light passes through the code disc and mask to split into different channel photo-detectors. The incremental rotary encoder produces two channel outputs usually called channel A and channel B in a square waveform. The outputs from Channel A and B have equal magnitude but different phase. Channel B is 90˚ phase lag compared to channel A. The phase lag is used to determine the rotational direction of the incremental rotary encoder. The phase lag of incremental rotary encoder is shown in Figure 2.9. Most incremental rotary encoders have an additional output called Channel Z. Channel Z is used as a zero reference point or as an index signal to represent the number of revolutions.

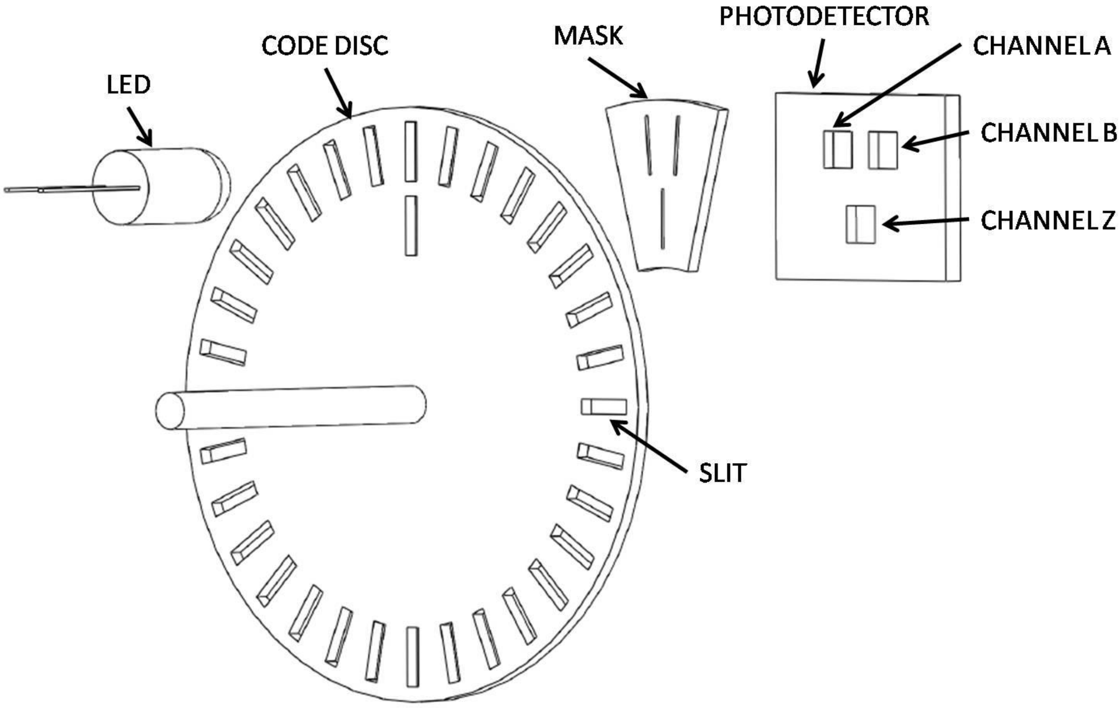


Figure 2.8: Incremental rotary encoder basic assembly diagram

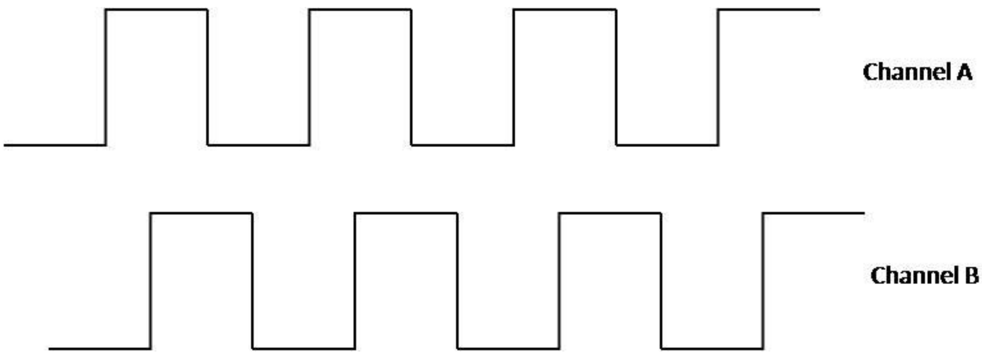


Figure 2.9: Output signals by incremental rotary encoder - channel A and channel B

2.5 DESIGN AND APPLICATION OF ROTARY ENCODERS

The needs for encoder is increasing from automation systems, motor feedback and flow control (Alex et al., 2008). Different applications of rotary motion sensing require different types of rotary encoder to optimize their performance. The design characteristics that need to be considered are: performance, types, classification (incremental or absolute), budget, signal conditioning and signal communications.

Performance of rotary encoder can be classified as: accuracy, repeatability, resolution and cyclic error. Accuracy is referring to the difference between actual outputs with ideal output signal. Repeatability is referring as tolerance to which the controlled motion can be repeatedly positioned to the same point in its travel. Resolution refers to number of measuring segments in one revolution of scale. Lastly, cyclic error refers to tare of error on each cycle motion. In precision motion control, accurate measuring position, repeatability in every cycle, high resolution and low cyclic error is important. For example, in pick and place machine, the precise angle is needed to control the motion with system ability to stop at the same encoder count time after time.

Two distinct types of rotary encoder have demands of very different applications. The types are: optical rotary encoder and magnetic rotary encoder. The optical rotary encoder is used for precision application such as machine tools, form measurement, wafer handling and inspection yet, the magnetic rotary encoder are often for physical demanding application such as torque sensing, industrial tools and factory automation (Alex et al., 2008).

The classification of rotary encoder is in two classifications: incremental and absolute. Each of its kind has its advantages and limitations. Incremental rotary encoder needs a signal counter in order to determine to exact location. For example, in x-y table machine during the power-up stage, x and y axis will move to limit position to set the reference position. Absolute rotary encoder does not need a counter. It can determine the exact position during the power-up stage. The absolute rotary encoder is suitable to implement in a robotic arm application whereas, it doesn’t need to find a reference point during power-up stage.

Budget consideration in selecting a proper encoder for optimum and suitable configuration is one of crucial part in a proper encoder application selection. With a reference from one of international trading company, ELEMENT14, cost comparison is shown in Table 2.1. The cost comparison is compared between encoder classifications with resolution of 256 pulses per revolution.

Table 2.1: Cost comparison between encoder

Encoder classification	Absolute	Incremental
Cost	RM 1414.79	RM 448.20

Signal conditioning is to maximize amplitude of the signal of interest while reducing the interference signal. There are two classes of signal conditioning that are: basic and advanced. Basic signal conditioning consists of offset adjustment, amplification and filtering while advanced signal conditioning consists of peak detection and precision rectification. Signal conditioning need to be considered in applying encoder to the system. Encoder signal can be encountered with a signal distortion and electrical noise during transmitting encoder signals. Signal line for an encoder should be shielded, twisted and routed in a separate conduit away from power leads to avoid signal interferences.

Encoder communications derives as an output signal from the rotary encoder to the receiving device. Incremental rotary encoder produces a stream of pulses through one, two or three channels, while the absolute rotary encoder produces a multi-bit word signal. The absolute rotary encoder can produce either in parallel or serial form. In parallel form, the outputs are either in gray code or binary code format. In serial form code, the parallel for of output is encoded and send it in serial form. The parallel form data are available in real time all the time but include bulky cables for each data bits.

2.6 FACTORS AFFECTING OPTICAL ROTARY ENCODER DESIGN FOR HIGHER PERFORMANCE

In designing higher performance optical rotary encoder, several factors are critical. Based on literatures and published patents in recent years, factors effecting optical rotary encoder design for high performance can be divided into five categories. The categories are:

1. Mechanical alignment of components in the optical rotary encoders
2. Resolution enhancement of the optical rotary encoders
3. Size reduction of the optical rotary encoders
4. The need for additional electronics in the optical rotary encoders
5. Other challenges for building the optical rotary encoders

2.6.1 Mechanical Alignment of Components in the Optical Rotary Encoders

Mechanical alignment is a major issue during assembly of component in the optical rotary encoders. Misaligned components will lead to incorrect functioning. The components involved in the alignment accuracy are: light source, motor shaft, pattern code disc and photo-detector.

The optical rotary encoders are able to generate light pulses with consistent phase when the alignment between the light source, the patterned code disc and the photo-detector is correct (Musha et al., 2008). Nevertheless, the assembly of the optical encoders involves many complicated steps (Igarasi and Iida, 2008). This increases the possibility of misalignment. Additionally, the light source, the patterned code disc and the photo-detector are assembled as different parts within the encoder (Ohmura et al., 2005). As highlighted by several researchers, misalignment often occurs because of (1) the deviation of the relative position between the shaft and the patterned code disc (Musha et al., 2008), (2) the deviation of the rotation axis between the shaft and the patterned code disc or eccentricity (Yoshioka, 2009), (3) the deviation of the relative position between the optical slits on the patterned code disc with the photo-detector (Musha et al., 2008), and (4) the possibility of creating dimensional deformation in assembly due to unwanted contact between the patterned code disc and the photo-detector (Hasegawa, 2009).

Misalignment in parts' assembly can substantially degrade the performance of the optical rotary encoder (Wong and Cheang, 2009) by disturbing the generation of stable light pulses when light passes through the patterned code disc. As a result, the photo-detector erroneously perceives the unwanted noises, which are added to the output of the photo-detector. This reduces the precision of the optical rotary encoders.

Besides, Sidor and Hinrichs (2009) and Villaret (2008) highlighted that the small eccentricity in the patterned code disc can be created during the assembly process. This factor limits the precision of the optical rotary encoders. An eccentric motion from its original position is not acceptable because the light beam is unable to intersect the patterned code disc at the position defined during the design stage. Eccentricity can happen because of errors in the dimension or their tolerance, which includes the tolerance error in the roll bearings that hold the shaft, and tolerance inconsistency in the patterned code disc. It is also caused by the improper radial alignment between the patterned code disc and the shaft. Apart from that, eccentricity is also generated from the invisible eccentric motion of the shaft when it rotates. This is known as wobbling (Sun et al., 2007).

In some cases, the relative position between the photo-detector, the light source and the patterned code disc is not consistent (Igarashi and Kamiyoshihara, 2008; Taniguchi and Aochi, 2001). This is because the position of the photo-detector is visually determined during the assembly process. Hence, it is difficult to establish perfect parallelism between the components. In view of this, the assembly process must be implemented with higher accuracy to ensure that the photo-detector receives a constant strength of modulated signals (Musha et al., 2008). This increases the total number of steps involved in producing the optical rotary encoder, which increases the cost of production (Igarasi and Iida, 2008).

2.6.2 Resolution Enhancement of the Optical Rotary Encoders

Resolution refers to the smallest position that the motion can be detected. With higher resolution, the detected motion becomes smaller. The standard rotary encoders are made with resolution range from 50 to 2,304,000 counts per revolution (Sclater and Chironis, 2007). There is an increasing trend for building the optical rotary encoders with higher precision in view that they are more frequently used in demanding applications (Chang and Kress, 2009). In the conventional optical rotary encoders, better precision in angular detection is usually achieved by increasing its resolution or by increasing the optical slit count (Wei, 2008). Nevertheless, it is not easy to achieve higher resolution for the optical rotary encoder due to several reasons.

Traditionally, the spacing of the optical slits on the patterned code disc is reduced to increase the resolution of the optical rotary encoders (Atsuta and Igaki, 2008). However, it is not easily done in practice (Villaret, 2008). This technique increases the chance of creating irregularity in such patterns which can generate unstable light pulses. In addition, as mentioned by Atsuta and Igaki (2008), when such spacing is reduced, the amplitude of signals obtained by the photo-detector becomes smaller hence reducing the capability of signals interpolation (Igaki et al., 2008a). Furthermore, it is also important to note that the diffraction properties of light become an upper limit to the number of optical slits allowable on the patterned code disc (Dumbravescu, and Schiaua, 2000). Also, there is a limit for the reduction of the distance between the optical slits in the fabrication process (Shimonaka et al., 1998).

Other than the physical build, the signals detection capability must be improved to achieve better resolution. This includes the use of signal interpolation techniques to increase the sensitivity of angular motion detection (Igaki et al., 2008b). Normally, the triangular or trapezoidal wave is generated when the photo-detector detects the light pulses. Nevertheless, such signals are not ideal for generating the finely divided signals which represents smaller angular displacement through signals interpolations. Particularly, the trapezoidal output signals are less preferable (Wong et al., 2008b). This is because the trapezoidal signals consist of a series of ramps, upside and downside while having a constant value as flat spot between each of them. At the constant value region, the photo-detector is unable to generate any useful information on the relative motion between the photo-detector and the patterned code disc. In addition, the ramp region within the trapezoidal signals is less differentiable as compared to the sinusoidal signals. Hence, it is impossible to derive the actual angular acceleration from the ramp region in the trapezoidal signals. Wong et al. (2008b) emphasized that a mechanism that generates the sinusoidal output signals is more preferable.

2.6.3 Size Reduction of the Optical Rotary Encoders

At this moment, the need for miniature optical rotary encoders is high. This is because the optical rotary encoders are often integrated into smaller devices such as cameras, mobile phones, etc (Bin Saiden et al., 2008). Miniaturization helps to create optical rotary encoders for use in smaller platform. Besides it increases the light beam from the light source intensity, enhanced responsiveness in detection as the result of the reduction in momentum (Cui et al., 2002). Hence, it has becomes increasingly important to design optical rotary encoders with smaller form factor. Unfortunately, there is a limitation in manufacturing to build optical rotary encoders in small size without compromising its resolution in angular motion detection and vice versa.

This issue is becoming worst in term of product manufacturing with the absolute optical rotary encoders. As mentioned by Oka and Ohmura (2006), the precision of the absolute optical rotary encoders are determined by two factors, which are (1) the number of tracks or the annular rings that represent 1 bit of solution each (in the radial direction) and, (2) the size of slit openings on the patterned code disc. The number of the slit opening on the patterned code disc must be increased in order to obtain higher resolution (Wei, 2008). Thereafter, additional tracks on the patterned code disc are required to achieve higher resolution. Furthermore, Toh et al. (2009) mentioned that the tracks on the absolute optical rotary encoders must be appropriately separated from each other, so that the light from the different tracks does not interfere with each other's. This inevitably increases the diameter of the patterned code disc which contradicts with the desire to reduce the size of the absolute encoders. Obviously, a trade-off must be made between the resolution and the size of the absolute optical rotary encoders. Otherwise, a new design that can obtain multiple-bit resolution with a reduced number of tracks is needed to achieve the goal mentioned (Toh et al., 2009).

In addition to the diameter reduction for the patterned code disc, Yoshioka (2009) mentioned that there is a need to reduce the distance between the light source and the photo-detector as another size reduction alternative. Nevertheless, such reduction causes unwanted mechanical interference within the encoder's structures for example unwanted contact between the components with the core metal and the packaging. Furthermore, there is an optical limitation in reducing the distance between the light source and photo-detector (Ohmura et al., 2005). This problem can be avoided by using an additional light shielding plate in the encoder. However, this technique increases the total components and cost within a single optical rotary encoder.

Cui et al. (2002) addressed the challenge of heat management in small rotary encoders. In particular, they stated that one of the important challenges for achieving size miniaturization is the ability to integrate proper heat control or heat dissipation techniques. Uneven heat dissipation in an optical rotary encoder can generate uneven expansion or contraction of one or more elements because of their varied Coefficient of Thermal Expansion (CTE). This will cause degeneration of optical properties. Furthermore, Cui et al. (2002) provided some examples for the source of heat, which includes (1) the heat generated by the light source, (2) the heat generated from the electric motor of the rotating object, (3) the ambient temperature in which the encoder is used, and (4) the electronic circuits that are integrated in (or on) the optical rotary encoder. Heat management is definitely one of the issues that need to be considered since the size reduction in the size of the optical rotary encoders apparently decreases the packaging materials that could act as the heat dissipator.

2.6.4 The Need for the Additional Electronics in the Optical Rotary Encoders

The performance of the optical rotary encoders is restricted by the capability of its electronic support system. As stated by Villaret (2008), the frequency of the electrical signals generated by the optical rotary encoder increases with its resolution. High frequencies electrical signals are difficult to be transmitted through wires, without the noises in the signals. The wires must be shielded in order to solve this problem, which causes a higher production cost. To solve this problem, serial communication can be used between the optical rotary encoder and the processor. Nevertheless, the direct shortcoming of this option is the need for additional electronic circuit that converts the electrical signals into the serial signals. The signals from the optical rotary encoder are in parallel form before converting it into serial form. Also, this option causes the delay in the signals detection by the processor. The delay is caused by the need to flush the signal out before generating new signal.

Apart from that, extra electronic circuit is needed to support the signals interpolation. According to Chong et al. (2008), an interpolation IC is used to achieve this purpose. Nevertheless, this requires a redesign of the PCB layout as well as the final package of the encoder. Also, this has inevitably increases the size and the unit cost of the optical rotary encoders.

Furthermore, the use of extra electronic circuit increases the power consumption. Particularly, high power consumption in the optical rotary encoders installed in the consumer products is highly undesirable (Morishita, 2000). This is because such device is often used in the outdoor environment, which relies on batteries as the main power supply. In order to allow the product to be used for a longer time, the power consumption must be minimized. Furthermore, the high power consumption generates excessive heat in the electronic module. Therefore, the use of the extra electronic circuit to support the higher resolution requirement and the move to conserve the power consumption in the device is contradictory with each other.

2.6.5 Other Challenges for Building the Optical Rotary Encoders

The encoder is often installed in poor environmental locations, for examples: areas of extreme temperatures, vibrations, dust, etc (Uchida, 1992). Therefore, the optical rotary encoders are consistently exposed to the external disturbances. For example, the mechanical vibrations and temperature fluctuations perturbs the reading accuracy of the optical rotary encoders (Wang et al., 2008). The optical rotary encoders also suffer from the assorted problems such as device aging, process and temperature drifts, optical contaminations and form of factors (Rai et al., 2009).

The unwanted reflection of light from the surface of the patterned code disc can affect the quality of the modulated light pulses (Oka et al., 2009; Wong et al., 2008a). In some instances, the light beams that falls onto the patterned code disc are being reflected in an unparalleled way towards the light source. The stray lights are further reflected by other components in the housing before returning to the patterned code disc. These lights may add another phase in the light pulses modulated by the patterned code disc, which could act as the phase cancelling portion when it reaches the photo-detector. This situation causes a loss of contrast between the image of light and dark region on the photo-detector (Foo et al., 2007).

Furthermore, difficulties exist in calibrating the optical rotary encoders. According to Klein (2001), the optical rotary encoders need to turn a complete round to detect the profile of the full light pulses. Nevertheless, it is inconvenient to make a total turn in certain applications such as the rotary encoders used in the wind direction indicator, or the rudder position indicator, joystick and other devices. Tullis et al. (2001) mentioned that the patterned code disc itself is a problem for the optical rotary encoders. The use of the patterned code disc increases the cost and the difficulty of manufacturing. For example, several meticulous and expensive steps are needed to form the slits on patterned the code disc (Taniguchi and Aochi, 2001). In addition, the existence of the code pattern is the root cause for other problems for example mechanical alignment. The encoders would become more robust in performance if the use of the patterned code disc is avoided.

2.6.6 Summary of Factors Affecting the Optical Rotary Encoder Design for Higher Performance

All factors can be summarized in the form of a fishbone diagram as shown in Figure 2.10. The figure highlights major components that are considered before designing a high performance optical rotary encoder.

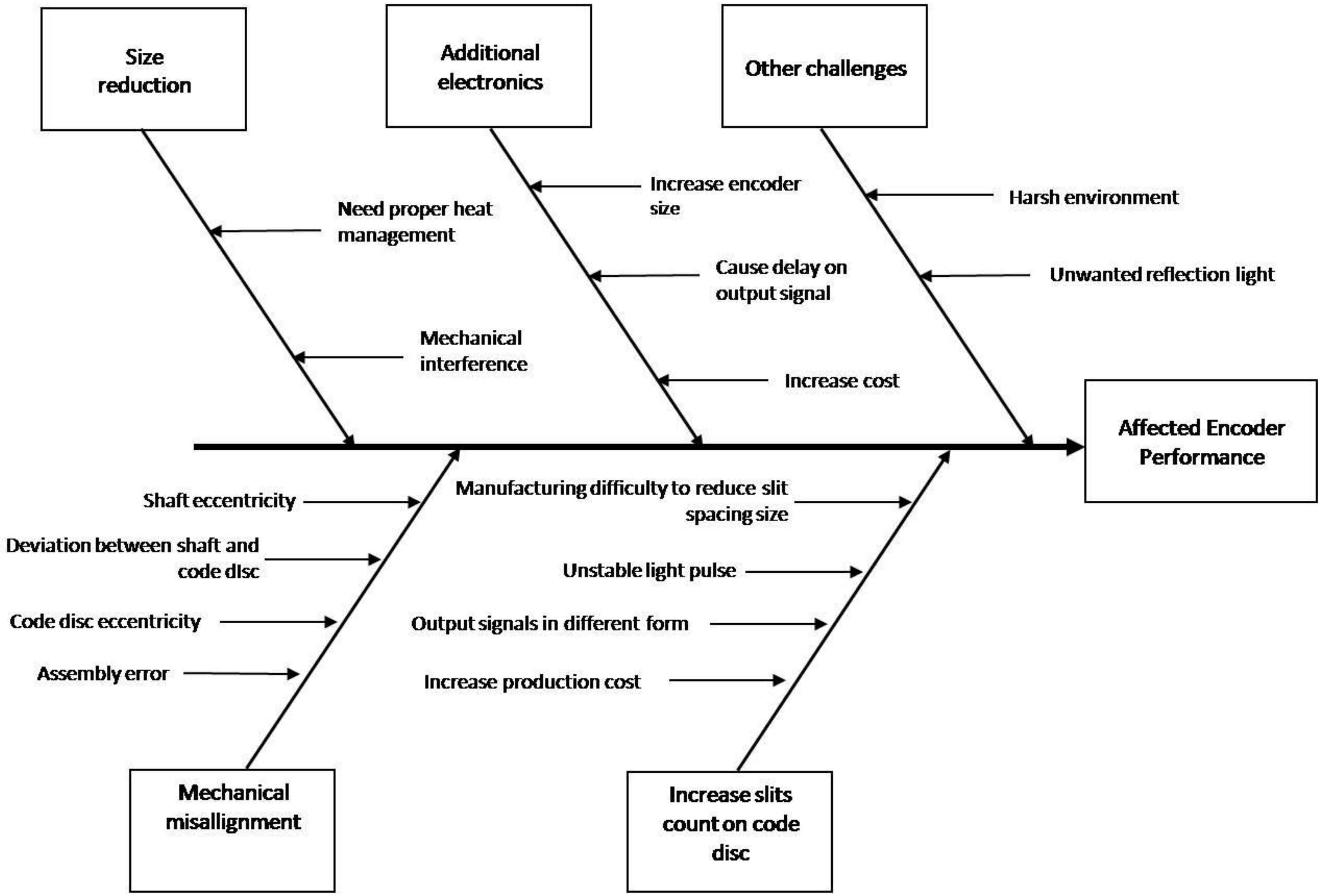


Figure 2.10: Cause and effect diagram for factors affect encoder performance

The entire factors that affect the performance of rotary encoder are mainly about the manufacturing difficulty, performance limitations, and high production cost in conventional optical rotary encoder. Therefore, new methods are needed to improve the limitations. The proposed method is to use an image sensor to replace the photodiode as well as a new design of the code disc. The advantage of using an image sensor is that it is a two-dimensional sensor compared to conventional optical rotary encoder which is a one-dimensional sensor. Using image sensor improves the area of detection.

2.7 PREVIOUS RESEARCH ON IMAGE ROTARY ENCODER

Various studies had been conducted in developing an image rotary encoder. Based on the previous studies, development of image rotary encoder can be classified into three areas which are: the sensing element, the code disc and the processing technique from the image. Three of the studies are presented in Table 2.2.

Table 2.2: Comparison of previous research on image rotary encoder

Sensing Element	Researcher	Year	Code Disc	Processing Technique	Limitation
Microscope optical system on a CCD array camera	Douglas B. L.	2000	Fiducial marking on the code disc	Using fiducial marking location	High cost on microscope optical system
Optical mouse sensor (ADNS 3088)	Tresanchez et al.	2009	White paper with single reference line	Incremental output using summation of pixel value	Error correction on each rotation
	Tresanchez et al.	2010	Printed code on white paper	Absolute output by locating pixel peak value	Not real time acquisition for absolute position decoding
BASLER camera	Wang et al.	2007	Axle head of servomotor	Processing rotary blurred images	For angular velocity estimation
Video measurement	Zhu et al.	2011	Straight line on image region	Comparing two adjacent frames of straight line	For angular velocity measurement

2.7.1 Microscope Optical System on a CCD Array Camera

This research is for ultra-high-sensitivity, incremental and absolute optical encoder (Douglas B. L., 2000). The system is using a microscope optical system on a CCD array camera that captures code disc pattern or scale. The pattern is made by unique fiducial markings on the code disc. The pattern is then analyzed by the image processor in order to locate the fiducial markings for decoding the position of the pattern. The decoding is done by counting the number of marks or pattern on the code disc.

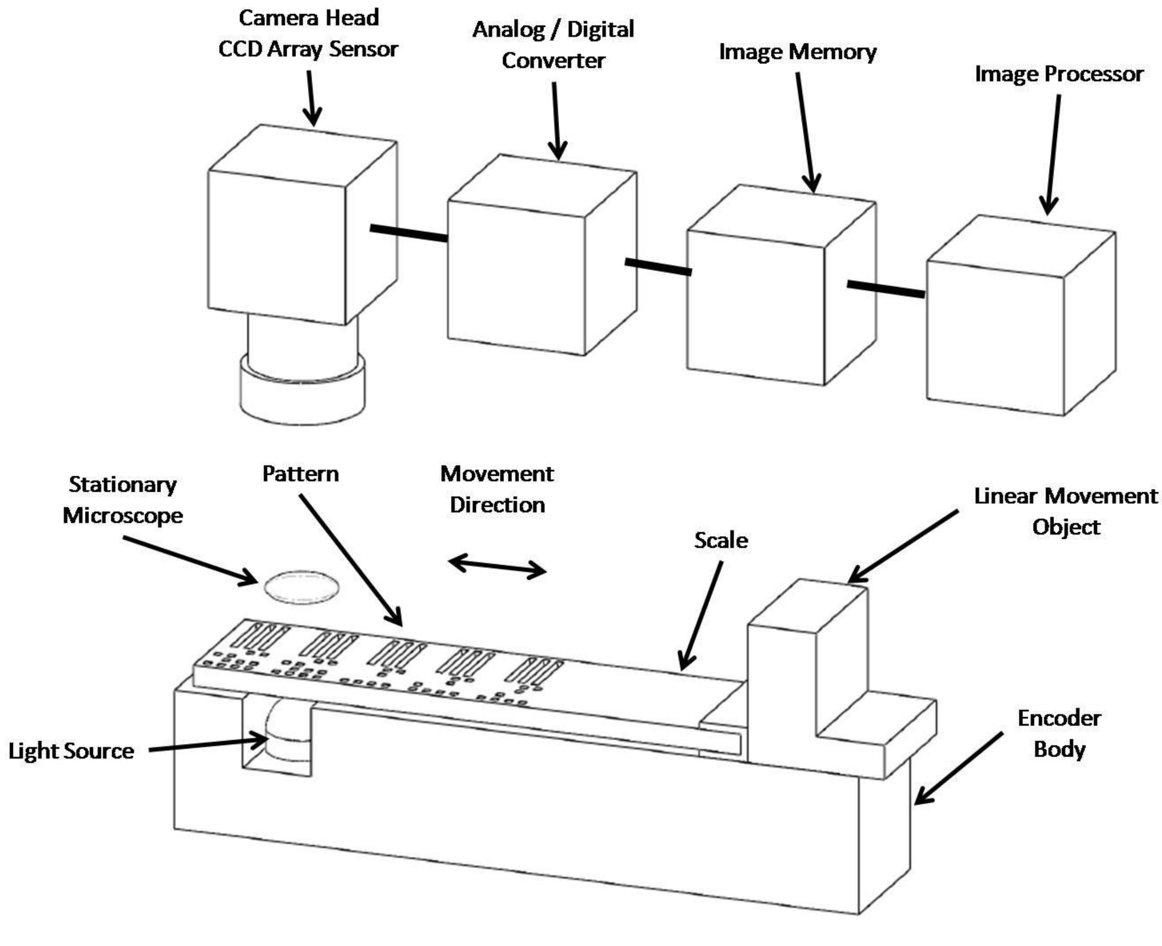


Figure 2.11: Schematic of an image encoder by Douglas B. L. (1999), United States Pattern

A schematic of linear encoder is shown in Figure 2.11. Light source is used for illumination of the scale. The illumination passes through the scale via pattern hole before colliding with stationary microscope. The light source projects portions of pattern onto camera head. In the camera head, CCD array sensor detects the image of the pattern in pixels form. Sample image taken form the CCD array sensor is shown in Figure 2.12. The pixels data is digitized by analog to digital converter. The output data is stored in the image memory before been analyzed by the image processor. Then, the image processor analyzed the data to produce an absolute position corresponding to the image taken. Linear movement object is attached to a scale and guided by a rail guide.

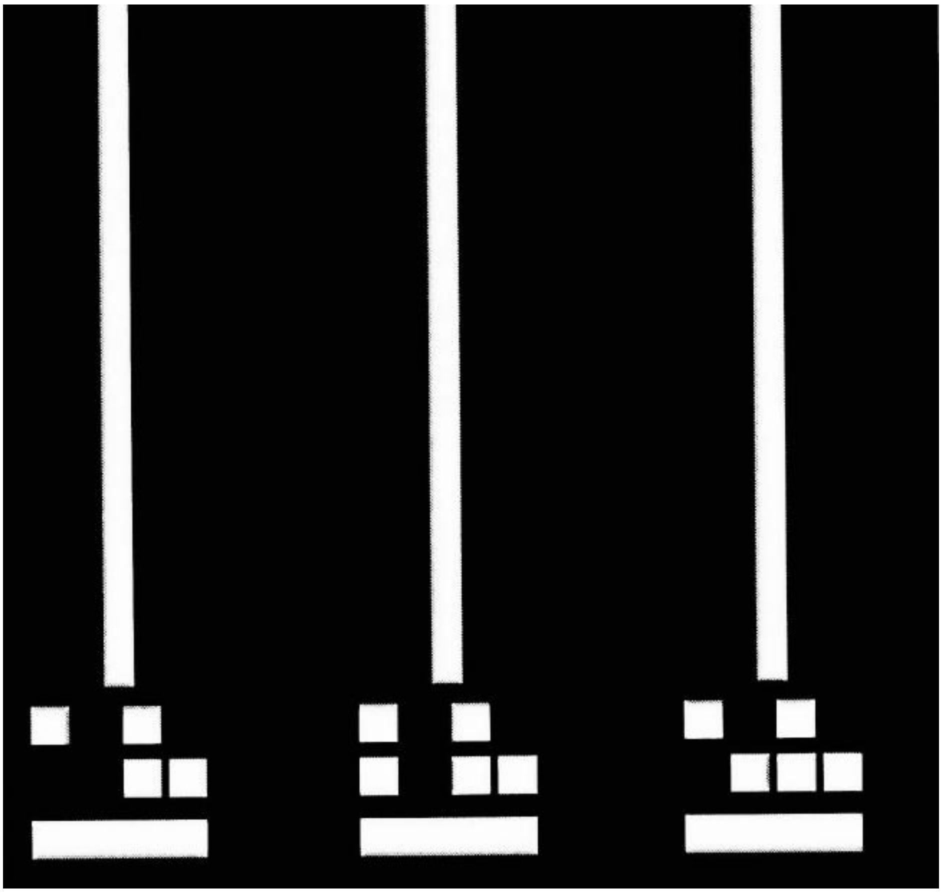


Figure 2.12: Scale pattern image

Source: Douglas B. L. (2000)

This research takes advantages of microscope optical system that can magnify the pattern. This will increase the resolution and encoding range of the encoder. The pattern can be made at the resolution of 5 μm. Despite these advantages, it comes with disadvantages of high cost for optical microscope system and a need for high precision alignment during encoder assembly.

2.7.2 Optical Mouse Sensor (ADNS 3088)

There are two research made by Tresanchez et al. (2009 and 2010b) for image rotary encoder. Both are for incremental and absolute rotary encoder.

The first research uses inexpensive optical mouse sensor as an incremental rotary encoder (Tresanchez et al., 2009). Optical mouse sensor has been used in robotics application (Palacin et al. (2006), Cooney et al. (2004)). It can be used as a measurement device for displacement and trajectory.

This research uses an optical mouse sensor, model ADNS-3088, that comes with digital image processor (DSP) and CMOS camera with 30 x 30 pixels frame resolution from Avago Technologies. It can go up to 6400 frames/second. A white paper is used as a code disc with a single reference line or radial line of width 0.2 mm. The radial line is used to accumulate the error for each revolution. Details of the code disc can be referred to Figure 2.13. The code disc surface is illuminated with an infrared light source. Average pixel value is used as the resolution of the incremental encoder. The average pixel value is the cumulative value of the pixels for the current image. The system can achieve resolution value close to 1900 counts per revolution for placement of the optical sensor 10 mm from the center of the code disc. The value will increase based on the placement of the optical sensor distance from the center of the code disc.

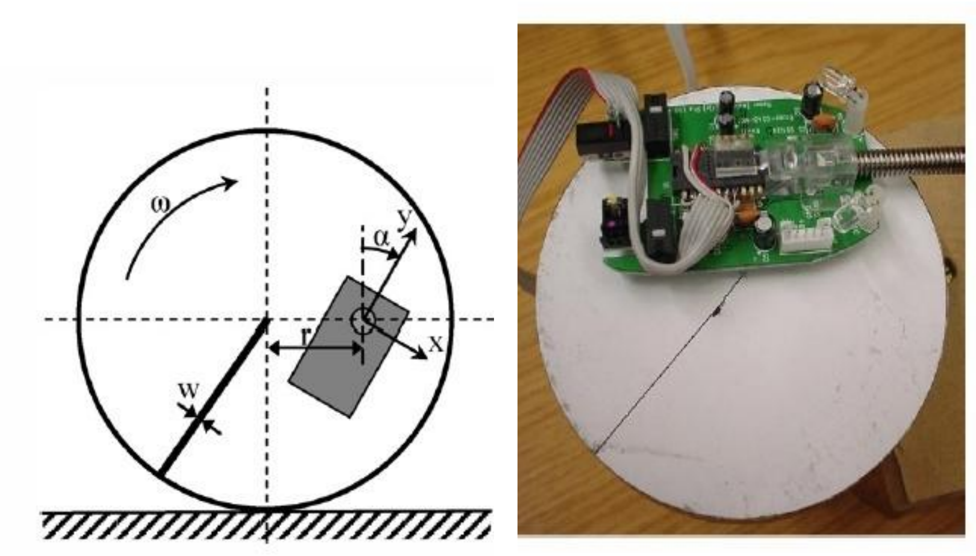


Figure 2.13: Image of prototype incremental rotary encoder using optical mouse sensor

Source: Tresanchez et al. (2009)

The drawback from this research is that, it needs error correction by detecting reference radial lines for each rotation to accumulate displacement errors. Somehow, the errors are lower than 1% for each revolution before resetting the cumulative error to zero when detecting the radial line.

The second research is an extended work by Tresanchez et al., (2009*)* to develop an absolute rotary encoder using the image acquisition capabilities of the optical mouse sensor as an image sensor (Tresanchez et al., 2010b) Most absolute rotary encoders use one pixel data to read a linear code on the code disc. Using an image sensor by the optical mouse sensor, two-dimensional matrix image data can be decoded. The detail of the prototype absolute rotary encoder can be referred to in Figure 2.14.

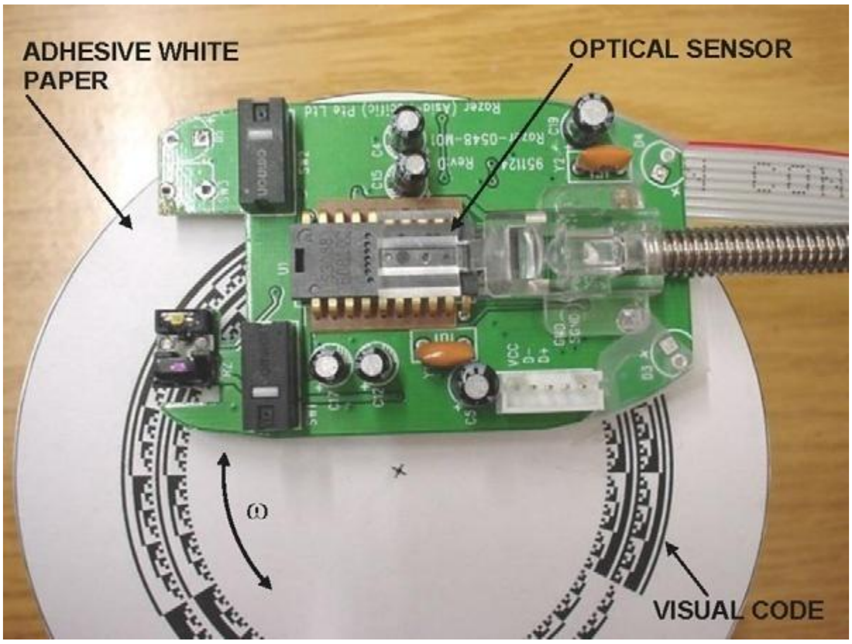


Figure 2.14: Image of prototype absolute rotary encoder using optical mouse sensor

Source: Tresanchez et al. (2010b)

This research uses the same optical mouse sensor from previously research by Tresanchez et al., (2009) model ADNS-3088 from Avago Technologies. The advantage of using optical mouse sensor is that, it has a short focal distance. The focal point recommended by Avago, (2009) is 2.4 mm from the surface. The optical mouse sensor is used to capture image of binary code printed on the code disc. The image is analyzed by locating pixel peak value of the binary code. Three decoding methods are proposed to analyze the image data: complete code, radial code and radial enhanced code. All the code represents a binary position for code information. The complete and radial code is in matrix form of 6 x 6 bits. The complete code is constructed from all the information bits available at the image to decode into a code for absolute position.

Figure 2.15 shows representation for complete code in 6 x 6 bits matrix. Arrows in the figure indicates the bits of the code. Bit with a black color represent "1" and empty bit represent "0". The radial code is using a portion of the image to analyze the code. The code for absolute position is arranged in a matrix form and is separated by three empty cells in a column. This will give advantages by using two dimensional image matrixes where more information can be stored for the absolute position.

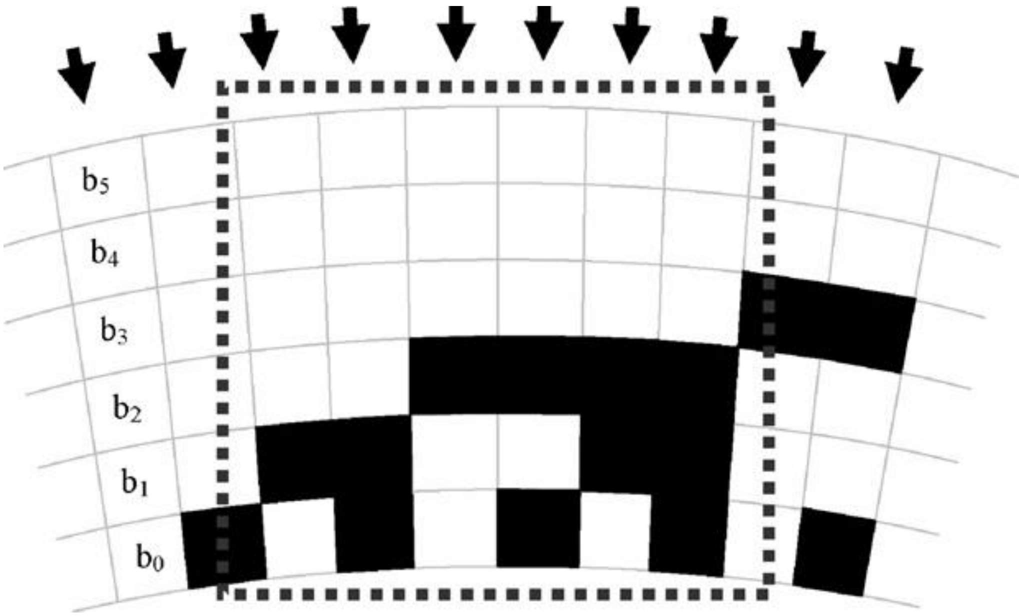


Figure 2.15: Complete code representation

Source: Tresanchez et al. (2010b)

Figure 2.16 shows representation for radial code in 6 x 6 bits matrix. Arrows indicate the position code information. The last code is a radial enhanced code that uses 9 x 9 bits of matrix. This method uses all bits information that is available on the image. One row is set to “1” as a reference line. Upper adjacent row is set to “1” as a reference bit for first column code location. Code information for absolute position is stored at upper adjacent row in three columns. Additional column is set empty for code separation before next code information. This will allow 21 bits codes to be stored in each one of code information. The code information can go up to 42153000 absolute positions for the placement of the optical mouse sensor at 407 meters from the center theoretically. The radial enhanced code can be represented in Figure 2.17 in 9 x 9 bits matrix.

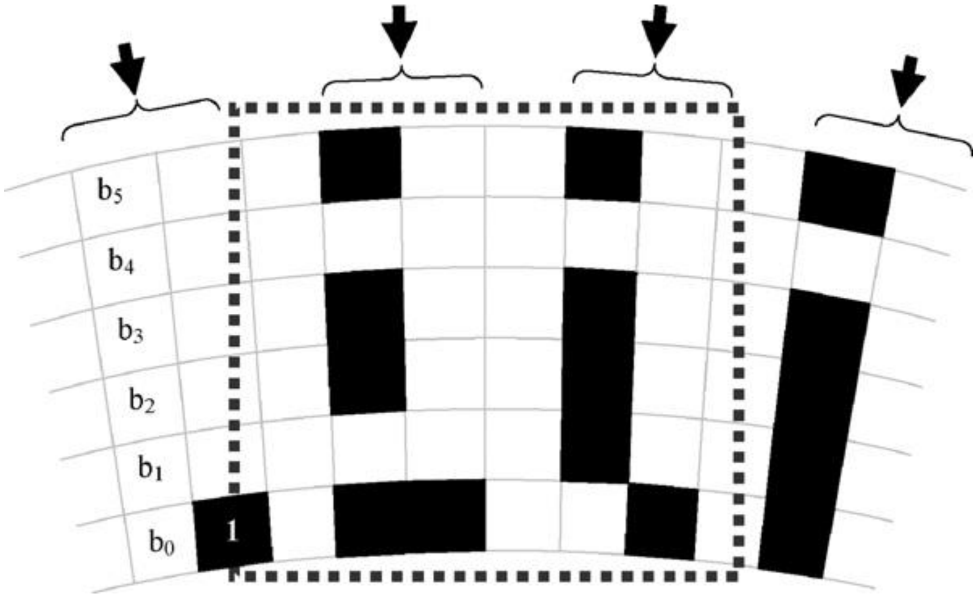


Figure 2.16: Radial code representation

Source: Tresanchez et al. (2010b)

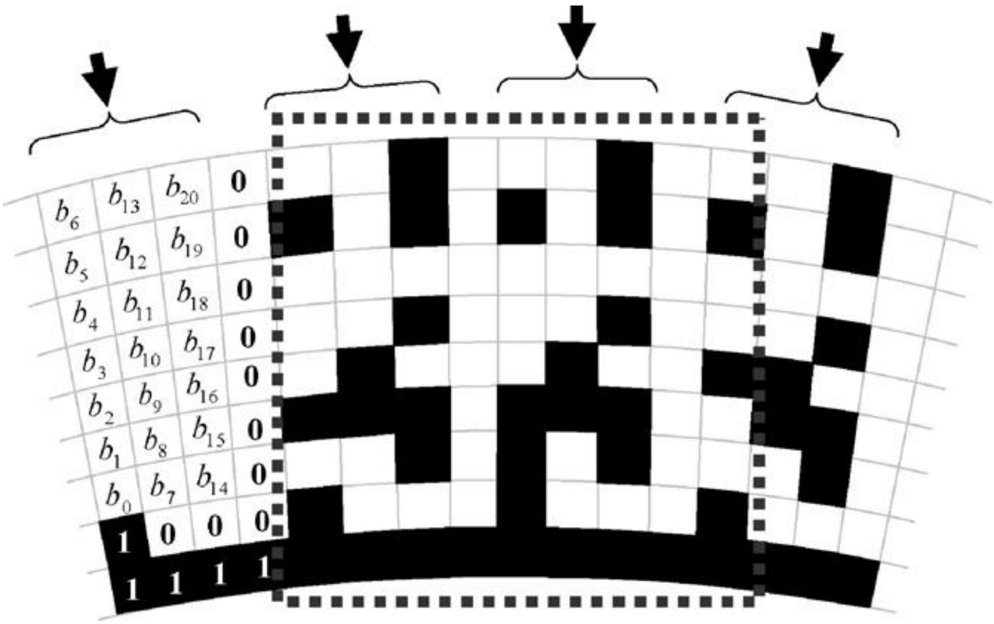


Figure 2.17: Radial enhanced code representation

Source: Tresanchez et al. (2010b)

All three decoding methods are used to maximize the code information for the absolute position. This will increase the resolution of the proposed absolute encoder. The resolution also depends on the placement distance of the optical mouse sensor to the center of the rotation. There are two techniques proposed for decoding the image information: combined and visual techniques. The combined technique uses image acquisition and automatic displacement measurement to determine the absolute position. The image acquisition is use for decoding the position based on the image acquired during no motion while automatic displacement measurement is used to determine the position during the movement of the code disc. The automatic displacement measurement can achieve sampling rate up to 6.6 kHz.

This proposed technique has a drawback of cumulative rotation error during the automatic displacement measurement. The error is reset during the stop motion when new image is acquired to determine the new absolute position. It’s not suitable for real time acquisition requiring absolute position.

The second technique is proposed by using visual mode where an image acquisition capability is only used. By using this method, the sampling rate has drop to 38 Hz maximum.

2.7.3 Basler Camera

This research is by a computer vision method based on image motion blur to measure of angular velocity (Wang et al. 2007). The system is consists of two components: computer vision system with a platform and motion generator system (Figure 2.18). The vision system is using a BASLER camera with an optical lens, adjustable focus and aperture that captures axle head of servomotor. The axle head of servomotor is a motion generator system that used to generate a blurred image.

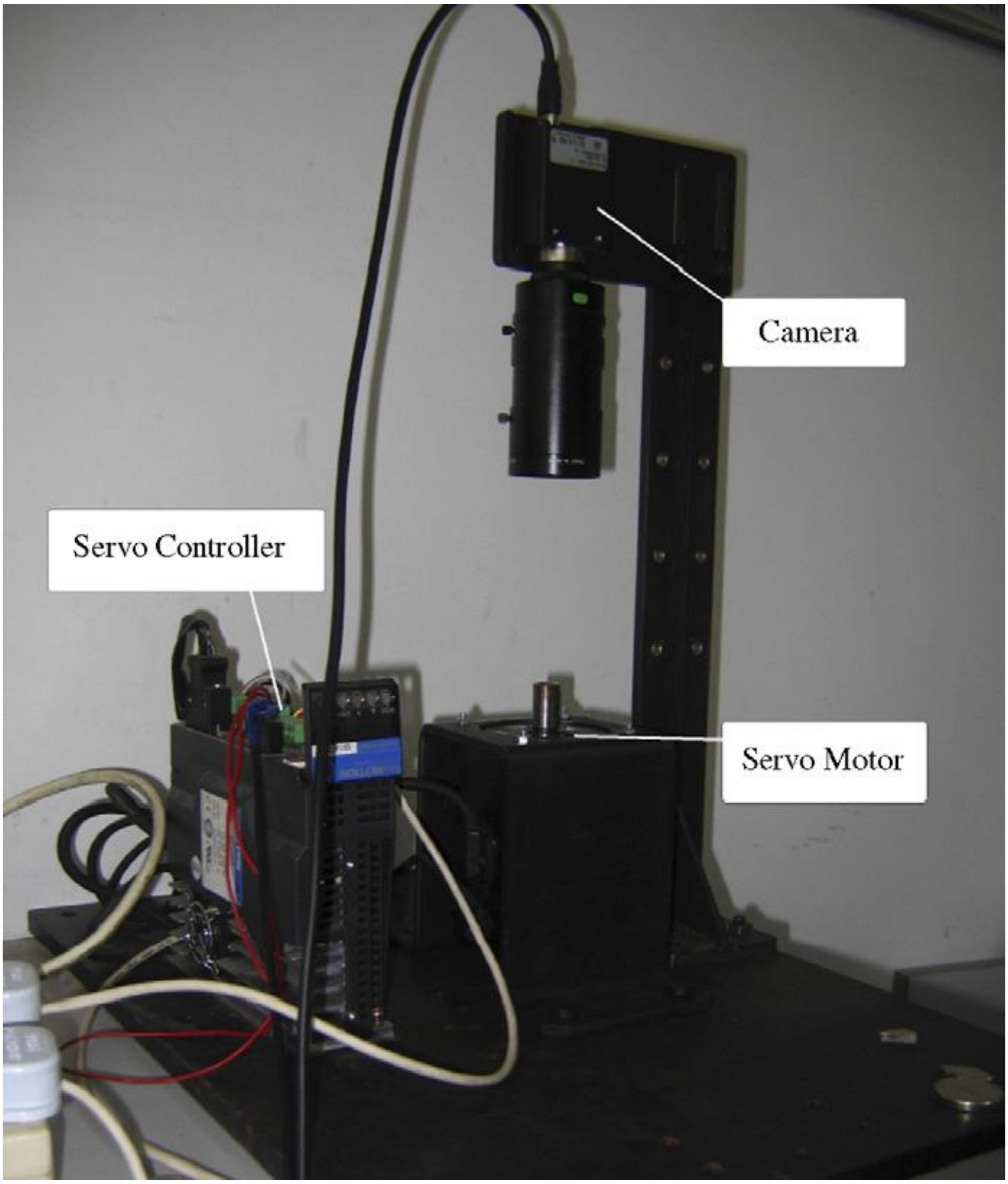
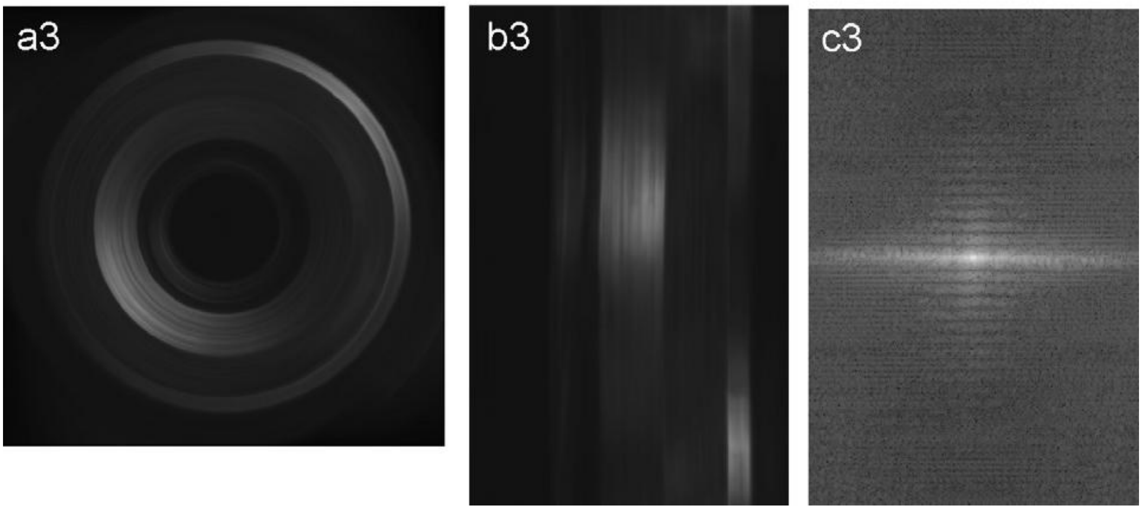


Figure 2.18: Experiment setup platform by Wang et al. (2007)

The image processing algorithm for the system is started by a polar transform is applied to the rotary center of blurred images. As the result, the rotary motion transform to translation. The rotary motions are in two dimensional rotations and are transforming to one dimensional translational motion by sectoring rotation blurred image. By using mathematical models in spatial and frequency domain to analyzed translation blurred images. The translation blurred images produced a series of dark parallel lines on the spectrum. It is related to the velocity translation and exposure time. The geometric relation is related to angular velocity. Figure 2.19 shown the rotation blurred image is transformed from the static image Figure 2.19(a) to one dimensional translational motion in Figure 2.19(b) to spectrum of blurred image in Figure 2.19(c) to calculate the angular velocity.



(a) (b) (c)

Figure 2.19: Transformation of blurred rotational image

Source: Wang et al. (2007)

This research takes advantages of rotation blurred image to estimate the angular velocity. Despite these advantages, it comes with disadvantages for angular velocity estimation only. The system did not been applied for motion control.

2.7.4 Video Measurement

This research is by a video measurement technique where a camera records a rotational movement of the objects and two adjacent frames are extracted to get the angular velocity (Zhu et al. 2011). Figure 2.20 is shown the concept of the system. A camera is recording a rotational motion of a straight line. Then, two adjacent frames are extracted from the video. By applying a Hough transform to detect the straight line in the images, the angular of each line can be calculated. Angular velocity of the object can be calculated by knowing the interval time of the two frames and the value of difference angle between the two frames.

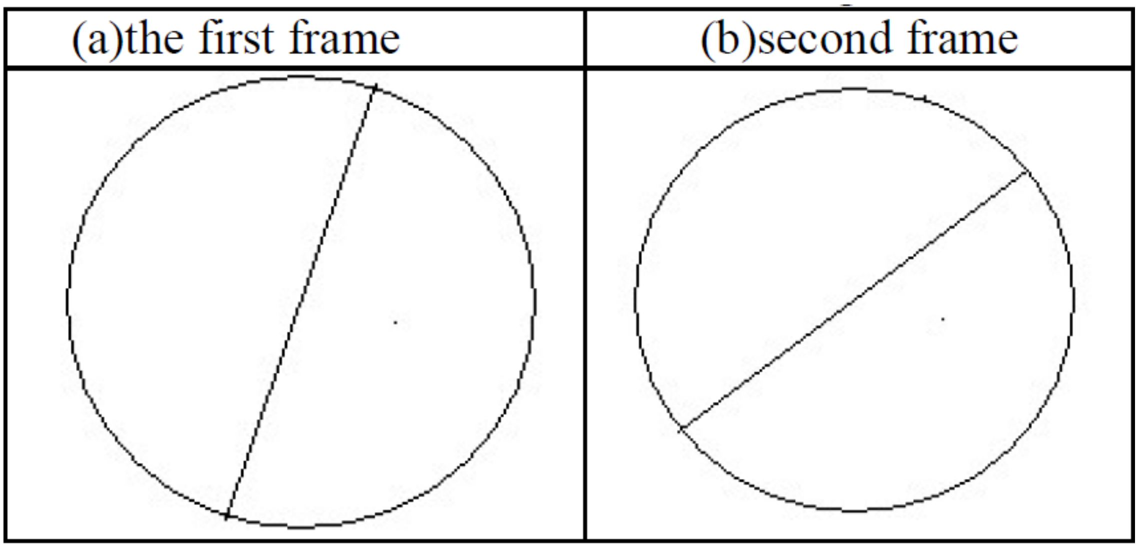


Figure 2.20: Two adjacent frames

Source: Zhu et al. (2011)

The research disadvantages cause by the video measurement where it is not for a real time video measurement.

2.7.5 Research Summary on Image Rotary Encoder

All researches are done by replacing the conventional sensor with an image sensor. Textures of the code disc are designed for the better usage of code disc surface. By using an image sensor, the frame rates affect the frequency of data taken. Research by Douglas B. Leviton (2000) requires high precision machining to make the fiducial marking. The system also involves high cost for the microscopic optical system. Research by Tresanchez et al., (2009) is low cost solution because of using inexpensive optical mouse sensor but the system requires error correction on every revolution by detecting a radial line. Research by Wang et al. (2007) and Zhu et al. (2011) is implemented by a video measurement technology. The research is not implemented for position feedback information.

To overcome the limitations of high cost image sensor by using a sophisticated optical system and the manufacturing difficulty in code disc development, new design of image rotary encoder are needed by using inexpensive image sensor and simplicity in code disc design. Improvement of image processing technique is the advantages of using an image sensor. The code disc design also can be simplified with the use of image processing technique.

2.8 RESOLUTION IMPROVEMENT BASED ON VELOCITY ESTIMATION FOR ROTARY ENCODER

Rotary encoder resolution depends on the significant data on the code disc. For incremental rotary encoder, the resolution depends on the number of slits on the code disc of the encoder.

There are several literatures focusing to improve the performance of incremental encoder by velocity and acceleration estimation (Merry et al., 2007, Tanaka et al., 2008, Baser et al., 2010 and Merry et al., 2010). The estimation method can be categorized into two categories that are fixed time method and fixed position method. Fixed time method measures the counter value with a fixed time period. On the other hand, fixed position method measures the time required over a fixed amount of counts (also called as encoder event). Fixed position method needs high frequency clock in order to capture the encoder event. High frequency clock can improve performance of fixed position method (Tanaka et al., 2008) but relatively at low encoder frequency (Baser et al., 2010). High frequency for the encoder event can be achieved but with the high frequency clock which is not practical for many applications (Baser et al., 2010).

Fixed time method can be classified into three techniques that are predictive post-filtering techniques, linear state observers and indirect measurement techniques (Merry et al., 2007 and Merry et al., 2010). In predictive post filtering technique filters differentiated position signals. Linear state observers' technique relies on encoder position measurement without using a differentiated position signal. Example of linear state observers techniques are dual-sampling rate observers and Kalman filters. Dual sampling rate is done by predicting state variables based on angle at every sampling time on the encoder event and the correct error from the next encoder event (Kovudhikulrungsri and Koseki, 2006). Kalman filters technique (Buchnik and Rabinovici, 2004) uses a motor model in order to predict the position including the encoder errors. The last technique is an indirect measurement technique whereby proportional value is calculated when the indirect measurement cannot be obtained.

2.9 SUMMARY

In relation to the research objectives, followings are conclusions from this chapter.

- The proposed image rotary encoder is developed because image rotary encoder is a viable alternative to conventional absolute rotary encoder,
- Since the research objective is to develop an algorithm based on digital image processing, in this chapter, various researches on image rotary encoder are discussed for research clarifications and guidance.

In the next chapter, detailed methodology in developing the proposed image rotary encoder is presented.

CHAPTER 3

HARDWARE AND SOFTWARE DESIGN OF IMAGE ROTARY ENCODER

3.1 INTRODUCTION

This chapter highlights the techniques and methods employed to develop an image rotary encoder for motion control. Details of the methods will be given in the following sections. The main objective of the proposed image rotary encoder is to develop an image rotary encoder using an image sensor as a sensing element.

3.2 DESIGN CONCEPT

The developed image rotary encoder utilizes series of captured images before analyzing it through a proposed algorithm in order to determine the positional output. The outputs are in the form of absolute position which is similar to the output of the optical rotary encoder. The proposed image rotary encoder can be divided into three main areas: sensing element, code disc design and output data processing techniques. It started with the development of hardware consists of: selection of sensing elements, placement of sensing element and the code disc design. Finally, the development is on the processing technique which is under software development.

3.3 SENSING ELEMENTS

The developed image rotary encoder is using a Logitech webcam camera model Webcam C210 with 640 X 480 pixel-resolutions and with the rate of 30 frames per sec. It is a low cost device that communicates using universal serial bus, USB. A Logitech webcam is shown in Figure 3.1.

Figure 3.1: Logitech C210 webcam

3.4 CODE DISC DESIGN

Figure 3.2 showed the full view of the image rotary encoder prototype. It consists of three major components: DC motor for rotating the code disc, Image rotary encoder prototype and conventional encoder for validation. The detailed design of the image rotary encoder prototype is shown in Figure 3.3.

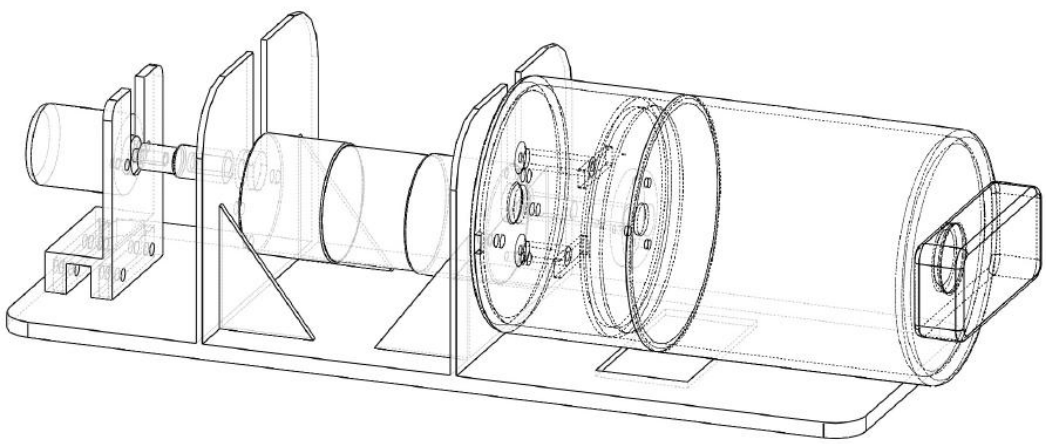


Figure 3.2: Full view of CAD image rotary encoder prototype

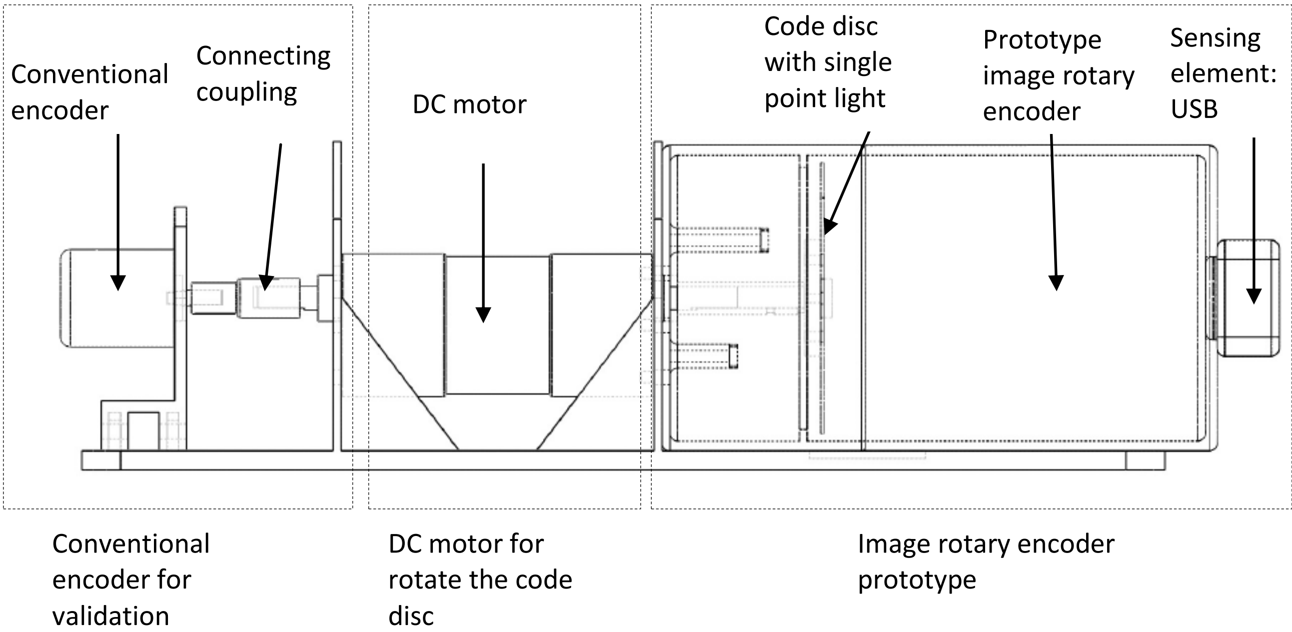


Figure 3.3: Front view of CAD model image rotary encoder prototype

Based on the design concept, the development started with the computer aided design, CAD and the CAD model for the prototype development. The image rotary encoder is designed to view all areas of code disk. The code disk is equipped with a single point light source where the light location will determine the exact position of the disk rotation (Figure 3.4). A hole of 0.2 mm diameter located at the single point of light location and a light source is attached at the back of the hole on the code disc. The single point of light will pass through the hole. The hole size is selected to 0.2 mm because of it is a smallest size of the single point of light that can be detected during the motion by the camera. The camera region from Figure 3.4 is referred to the area of view of the camera that is a top view of the system. The single point of light source is moving in a circular direction while at the same time using the centre point of the disk as a reference to determine the angle of rotation of the disk. The single point of light source is attached to the code disc with an external power supply is supplied to light-up the light source. Mechanism to transfer the power supply to the light source is by a brush touched to the shaft to make the power supply supplied the power during rotational motion.

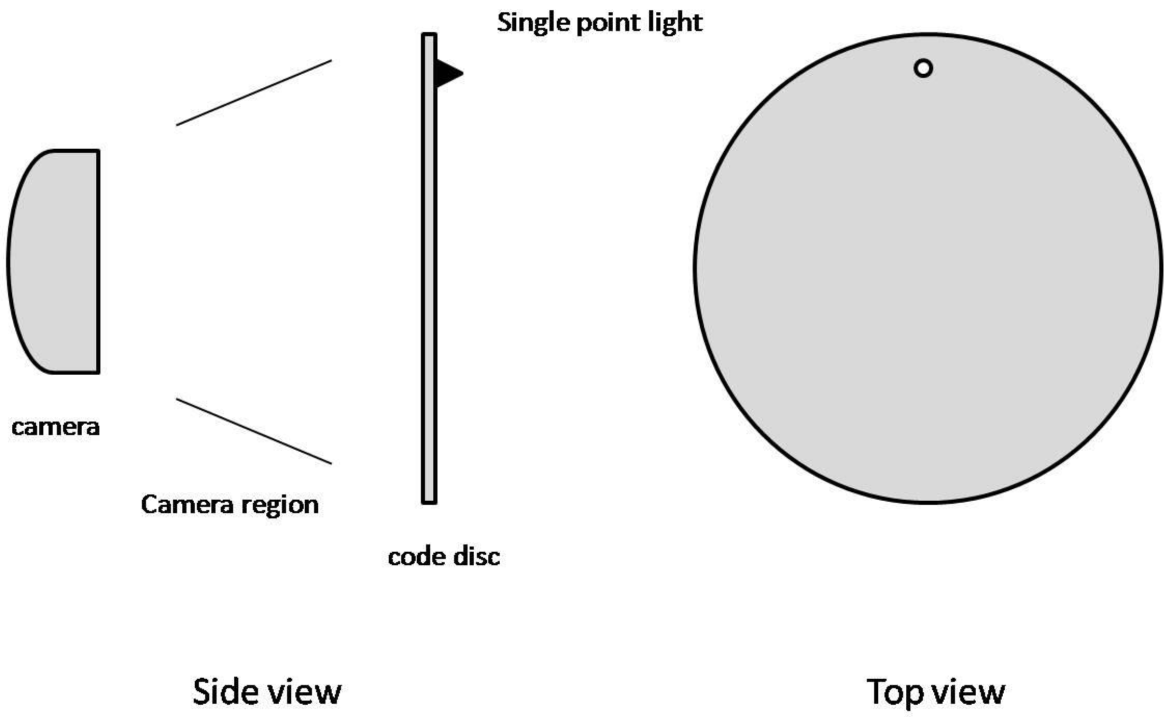


Figure 3.4: Code disc design concept

Figure 3.5 (a – i) showed the image sequences that were captured with a single point of light rotated in a circular pattern. The image was taken with a difference delay time. The difference delay time of the images captured is to represent the image in a rotation motion where the motion is in anti-clockwise rotation. Algorithm in processing the single point light will be based upon the centre of the circle as reference.

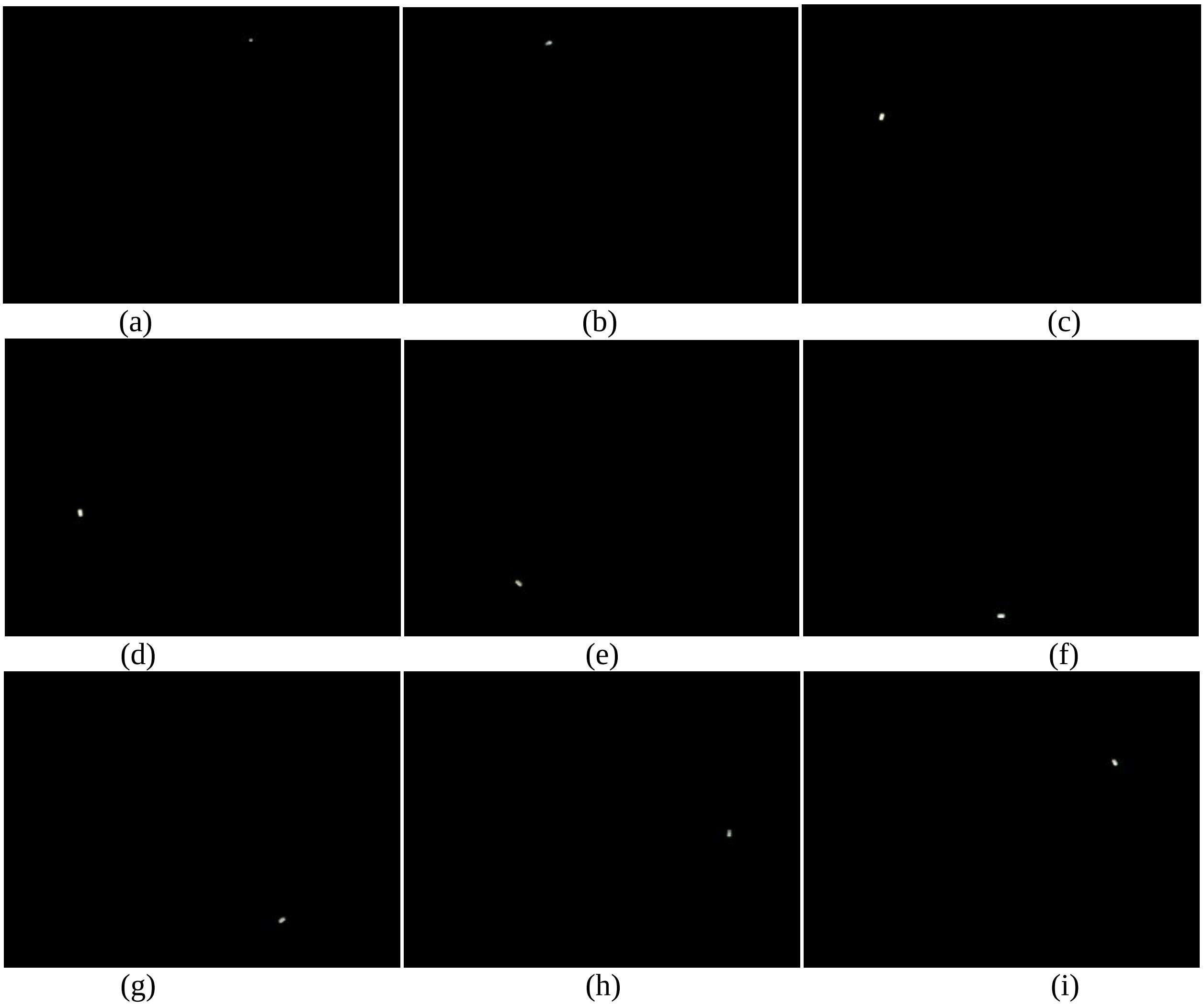


Figure 3.5 (a - i): Image taken from prototype code disc

3.5 OUTPUT DATA PROCESSING TECHNIQUES

The captured images were analyzed using image processing methods. To analyze the image, the OpenCV platform is used. OpenCV is an open source computer vision library that is written in C and C++. It can operate using Linux, Windows and Mac OS X. Figure 3.6 shows the algorithm flowchart to process the captured image.

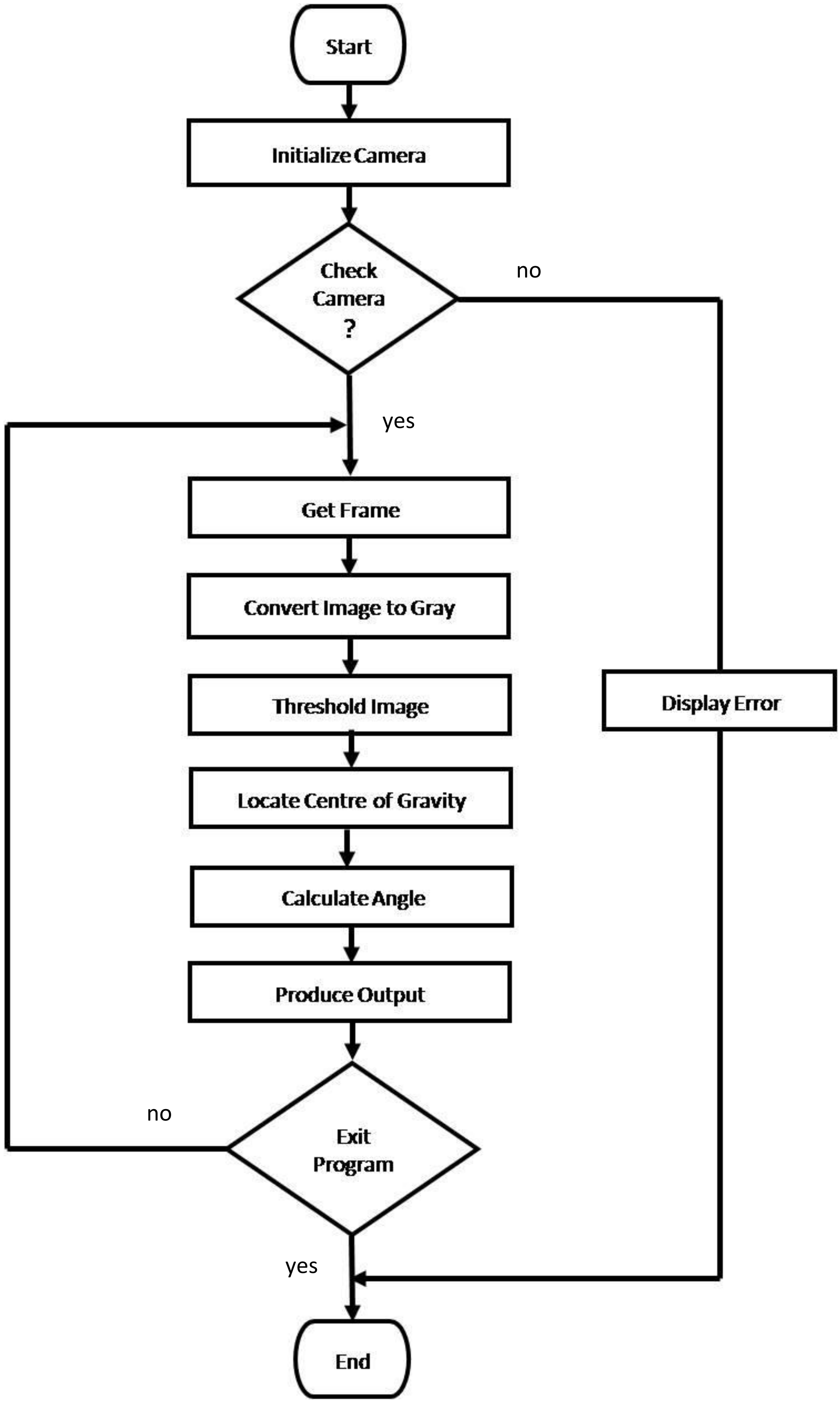


Figure 3.6: Flow chart of the algorithm

The purpose of the image processing used in this prototype is to give an output in terms of absolute binary position from the captured image.

3.5.1 Initialize Camera

After initializing a lookup table, to get the image the program needs to initialize the source of the image. The source of the image is from the webcam. Code to initialize the source is given below.

```
CvCapture *capture = 0;

capture = cvCaptureFromCAM(-1);
```

3.5.2 Check Camera

A camera check function is used to check communication between the camera and the program. If there is failure to communicate between the camera and the program, an error warning will be displayed. The checking procedure is done by the code below.

```
if (!capture)

{

      fprintf(stderr,   "!!!   Cannot   open   the   initialized
webcam!\n" );

      return -1;

}
```

3.5.3 Get Frame

Raw images from the webcam are captured and stored into frame images before further image processing can be done on the image. First, the frame image is declared to allocated memory space for the image data structured. Then, the current webcam image is stored on the frame image. The code is shown below.

```
IplImage* frame = 0;
```

```
frame = cvQueryFrame(capture);
```

3.5.4 Convert Image to Gray

The retrieved frame is in color form. It consists of three color channels: blue, green and red. The frame image then is converted to gray image by mixing the three color channels with specific ratio on each channel to produce one channel gray color. The new gray image is in one color channel with the same size of captured images. The conversion ratios are: 0.114 for blue, 0.587 for green and 0.299 for red. This calculation is done on every pixel of the image. The piece of code below is used to convert the color image to gray scale image.

```
IplImage* gray_frame = 0;

gray_frame = cvCreateImage(cvSize(frame->width, frame->height),
frame->depth, 1);

BwImagegray_frameA(gray_frame);

RgbImageframeA(frame);

for(inti=0;i<frame->height;i++)

    for(int j=0;j<frame->width;j++)

    {

          gray_frameA[i][j]= (uchar)(frameA[i][j].b*0.114 +
          frameA[i][j].g*0.587 + frameA[i][j].r*0.299);

    }
```

3.5.5 Threshold Image

Thresholding function is to produce a two-level binary image - either dark or light. The function categorizes the image by rejecting those unwanted pixels below or above some value while keeping the others. By using binary threshold function, threshold value is set to 200. The value of each pixel that is below 200 is set to zero while the value that is above 200 is set to one. Threshold value of 200 is experimentally set based on the stray light conditions or unwanted noise from the point of light on the code disc. The code for thresholding can be referred below.

```
IplImage* thresh_frame = 0;

thresh_frame = cvCreateImage(cvSize(gray_frame->width,
gray_frame->height), gray_frame->depth, 1);

cvThreshold(gray_frame,thresh_frame,200,255,CV_THRESH_BINARY);
```

3.5.6 Locate Centre of Gravity (COG)

After thresholding, the image is considered as a single point of light. This is represented by a binary image data whereby the white color represents one and the black color represents zero. This data is used to find the center of gravity, COG of the single point of light. The COG represents the absolute pixel location for the single point of light. It can be determined by using the contour-moment function.

The contour-moment function is already available inside the OpenCV platform whereby its calculation is based on Eq. (3.1) below.

$$m_{p,q} = \sum_{i=1}^{n} I(x,y)x^p y^q \tag{3.1}$$

The function is used to compute the area of non-zero pixels by calculating the moment on the two axes - x and y axis. The *p* and *q* are x-order and y-order which is the power corresponds to the component that is taken in the sum of all pixels. The moment is the length in pixels of the contour for *p* and *q* whenever both are equal to zero. Code to locate the center of gravity is shown below.

```
CvMoments moments;

cvMoments(thresh_frame, &moments, 0);

double m00, m10, m01;

m00 = cvGetSpatialMoment(&moments, 0,0);

m10 = cvGetSpatialMoment(&moments, 1,0);

m01 = cvGetSpatialMoment(&moments, 0,1);
// TBD check that m00 != 0

intcenter_x = m10/m00;

intcenter_y = m01/m00;
```

3.5.7 Calculate Angle for Binary Positioning

With the single point rotating light, the angle of the point location to the reference line can be calculated by using an arc tangent function. The representation of the circular trajectory is shown in Figure 3.7. The COG provides *x* and *y* location of the image for the single point of light. Angle, θ of the COG relative to the centre of the circle and is expressed as in Eq. (3.3). The angle is calculated from the reference line to the COG.

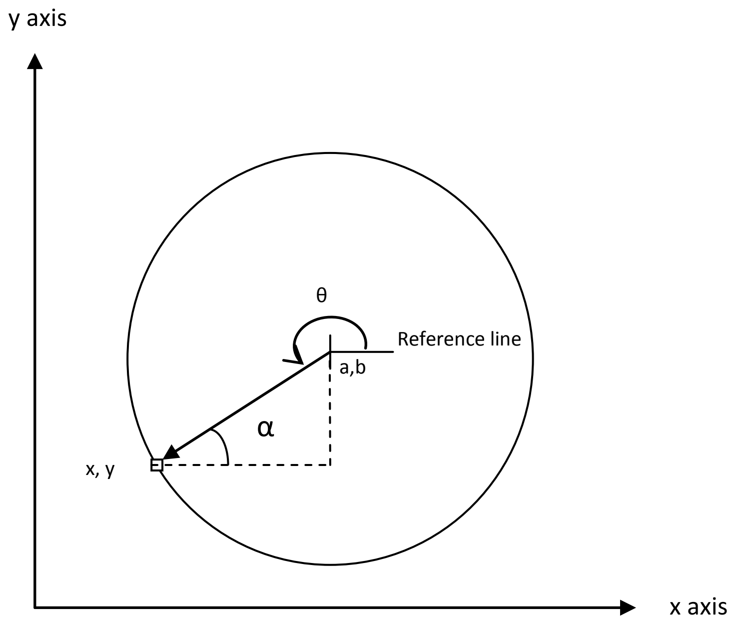


Figure 3.7: Circular trajectory representation

$$\tan\alpha = \frac{b-y}{a-x} \tag{3.2}$$

$$\theta = 180^\circ + \alpha \tag{3.3}$$

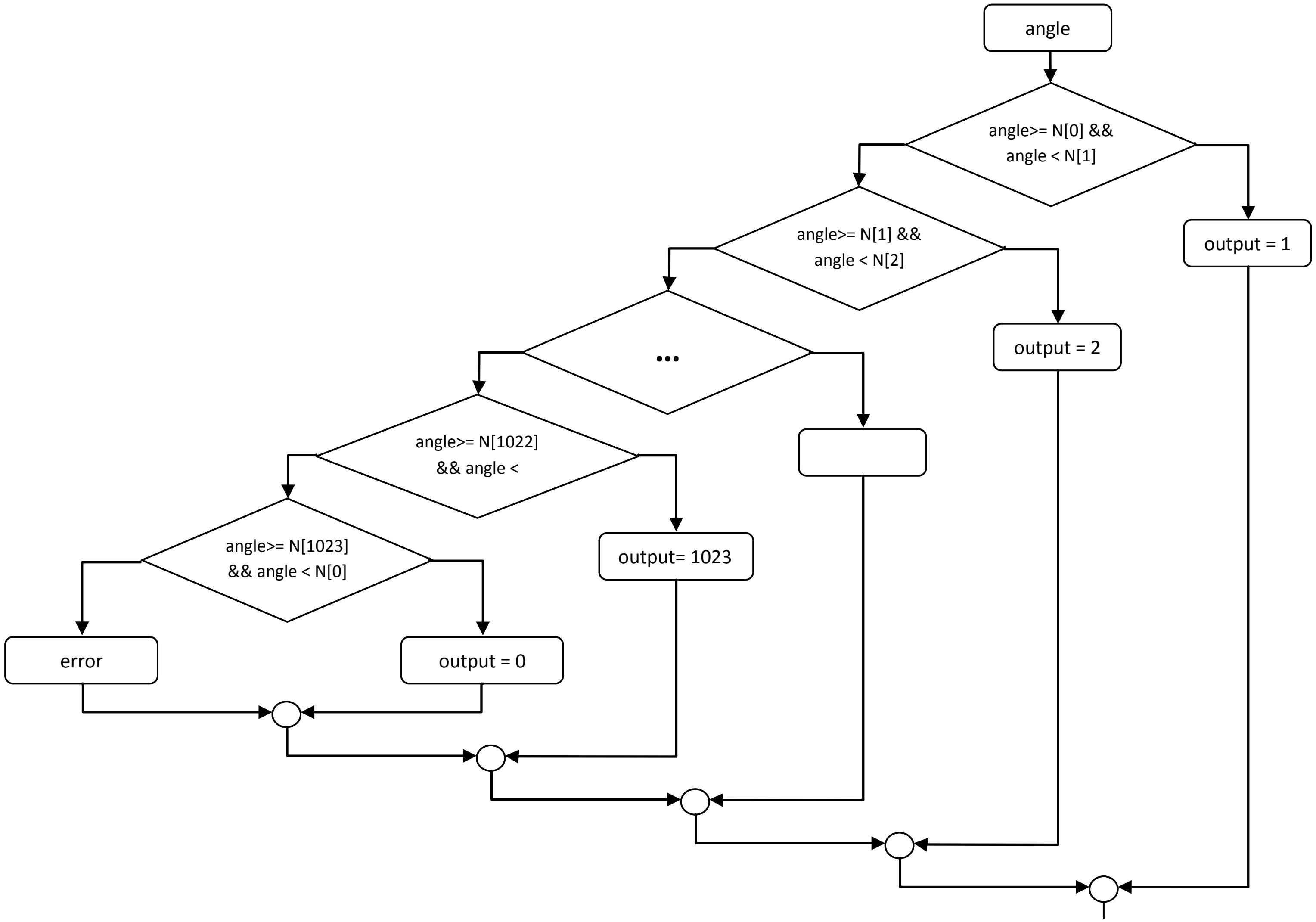


Figure 3.8: The *else* - *if* logic designs for determining binary position

Based on the logic diagram Figure 3.8, the binary position is produced based on the angle range. Each angle range is equivalent to 0.3516°. The *else-if* logic design statement is a multi-way decision. It is coded by the first *if* condition and its associated statements, and then follow it with all other possible values using *else-if* statement. The last test in the series concludes with an *else* statement as a default condition. The COG value is compared between the range values in order to determine the output data.

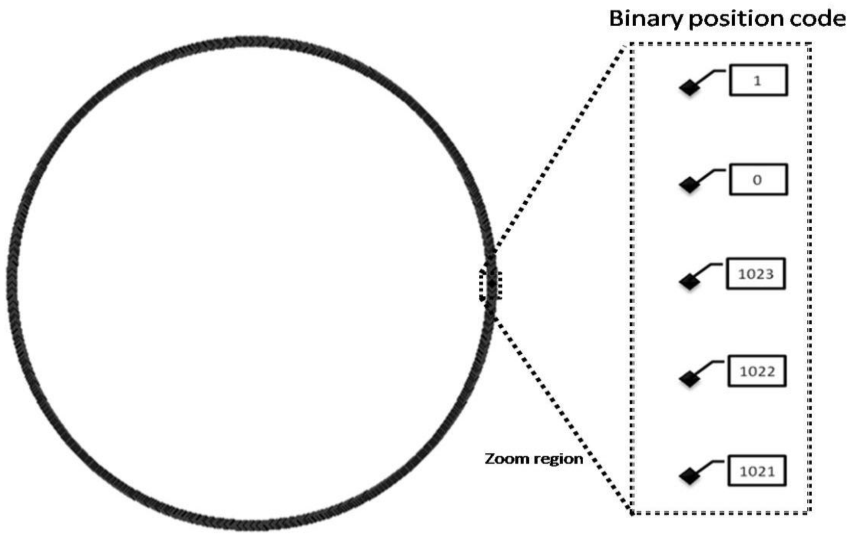


Figure 3.9: Binary position representation in zooming mode

The calculated value is in radians and then converted to binary position. The binary position is a code to represent its absolute location. Figure 3.9 shows the representation of the binary position code in zooming mode. Each location is assigned with a specific binary position code. The code to decode the angle to produce the output is shown below.

```
intcheck_point(intcenter_x, intcenter_y)
{
   int output;
   float angle_a,angle;
   intc_x = 0;
   intc_y = 0;
```

```
    float N[1024];

    angle_a = ((atan2(center_y-c_y,center_x-c_x))*(180/PI));

    angle = 90 - angle_a;

    if (angle_a< 0)
      angle = 360 - angle_a + 90;

    if (angle >= N[0] && angle < N[1])
      output = 1;

    else if (angle >= N[1] && angle < N[2])
      output = 2;

    ...

    else if (angle >= N[1020] && angle < N[1021])
      output = 1021;

    else if (angle >= N[1021] && angle < N[1022])
      output = 1022;

    else if (angle >= N[1022] && angle < N[1023])
      output = 1023;

    else if (angle >= N[1023] && angle < N[0])
      output = 0;

    else
      printf("%Error\n");

    return output;

  }
```

3.5.8 Produce Output

In order to function like the optical rotary encoder, output from the image rotary encoder is converted to the standard form. The standard output form is square waveform with three output channels for incremental rotary encoder or a binary code output for the absolute rotary encoder.

For the proposed image rotary encoder, the output is in the form of absolute rotary encoder. The output size is 10-bits with resolution equivalent to 1024 absolute position. The output data is transmitted through the enhanced parallel port, EPP. Figure 3.10 shows pins configurations for the parallel port. There are 25 pins all together. The 25-pin represents four main functions: data register, status register, control register and ground. Data register can be used as bi-direction input-output configuration, while the status port is used as an input configuration and control port is used as an output configuration. The rest of the pins, pin 18 to pin 25 are ground pins. These are computer ground.

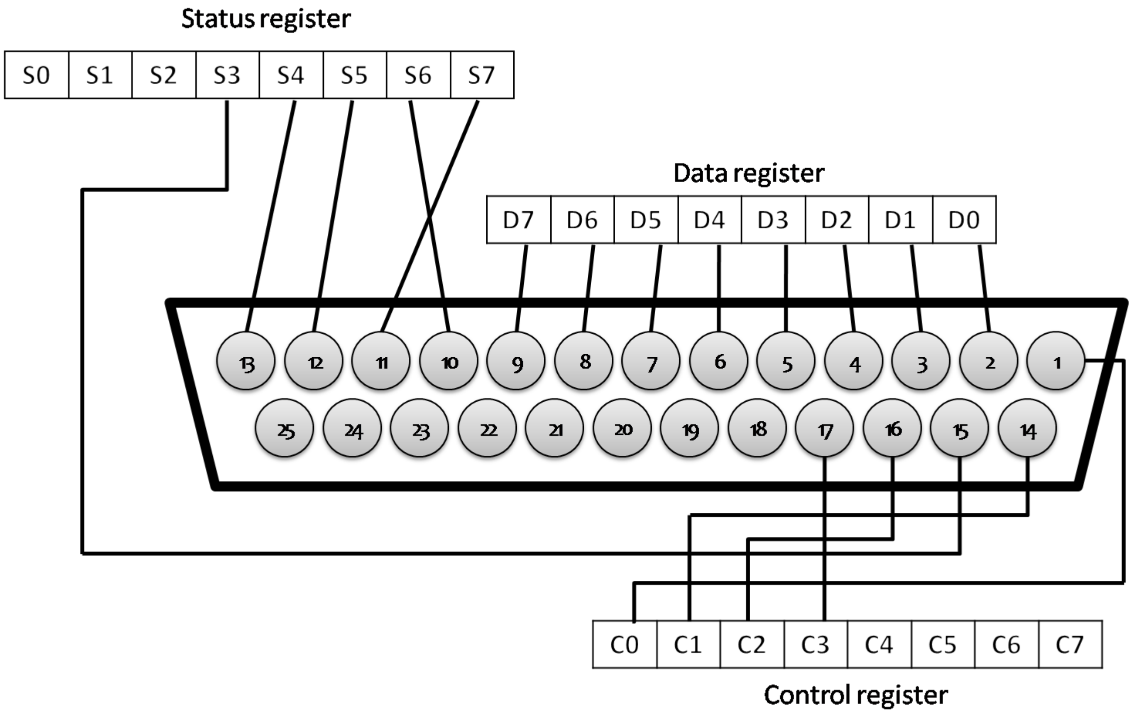


Figure 3.10: Parallel port pin assignation

Table 3.1 summarizes bit to pin mapping for parallel port. Symbol '~' represents the logic NOT function.

Table 3.1: Parallel port pin mapping

Decimal equivalent value	Bit value	Bit designation	Data port	Status port	Control port
			base	base+1	base+2
128	2^7	bit 7	pin 9	pin ~11	
64	2^6	bit 6	pin 8	pin 10	
32	2^5	bit 5	pin 7	pin 12	
16	2^4	bit 4	pin 6	pin 13	
8	2^3	bit 3	pin 5	pin 15	pin ~17
4	2^2	bit 2	pin 4		pin 16
2	2^1	bit 1	pin 3		pin ~14
1	2^0	bit 0	pin 2		pin ~1

The base value in Table 3.1 refers to the address of parallel port. Function to produce the output is started by receiving output data from calculated angle function named as *loc*. The binary position then is allocated to EPP port output. This is by combining data and control port to produce 10 bits digital data. Data port consists only 8 bits of digital data equivalent to 255 decimal values. Another two bits data come from the control port where bit 8 and 9 are allocated. Pin 8 and 9 are in inverse form. Designation of each bit can be referred to Table 3.2.

Table 3.2: Pin assignation for the experiment

Bits	**Bit 0**	**Bit 1**	**Bit 2**	**Bit 3**	**Bit 4**	**Bit 5**	**Bit 6**	**Bit 7**	**Bit 8**	**Bit 9**
Assign pin	2	3	4	5	6	7	8	9	1	14
Decimal equivalent value	1	2	4	8	16	32	64	128	~ 1	~ 2
Address	base	base	base	base	base	base	base	base	base + 2	base + 2
Value assign	1	2	4	8	16	32	64	128	256	512

Code to produce the digital output data is shown below.

```
voidoutput_out(intloc)

{

   output = loc;

   if (output < 256)
        {
          output_a = output;
          output_b = 3;
        }

   if (output > 255 && output < 512)
        {
          output_a = output - 256;
          output_b = 2;
        }

   if (output > 512 && output < 768)
        {
          output_a = output - 256;
          output_b = 1;
        }

   if (output >= 768)
        {
           output_a = output - 256;
           output_b = 0;
        }

        (oup32)(0xDD00,output_a);
        (oup32)(0xDD02,output_b);

   return;

}
```

3.6 SUMMARY

This chapter presents detailed processes in developing the image rotary encoder. It started with a design concept for the image rotary encoder. Then, the development is done by designing and selecting hardware component of the image rotary encoder. After the hardware, the software is developed using the OpenCV as a platform. Image processing algorithm is developed and carried out using C language with the help of OpenCV functions.

In the next chapter, the performance is validated by conducting experiments to compare with the conventional rotary encoder.

CHAPTER 4

EXPERIMENTAL VALIDATION OF THE DEVELOPED IMAGE ROTARY ENCODER

4.1 INTRODUCTION

In the previous chapter, detailed discussions on the development of image rotary encoder are presented. In this chapter, the developed image rotary encoder together with its algorithm is verified based on the position and speed measurement compared to the conventional optical rotary encoder. To ensure the effectiveness of the developed encoder, it is applied as an absolute position feedback device to a DC motor PID position control.

This chapter presents the objectives of experiments. Then, the experimental setup is described emphasising the roles of software, data acquisition and the hardware components. The issue of the algorithm processing time is discussed followed by the experimental validation between the conventional incremental rotary encoder with the developed absolute image rotary encoder – both for speed and position measurements. Lastly, this chapter presents the application of the developed image rotary encoder as a position feedback device replacing the conventional rotary encoder in implementing PID position control of a DC motor.

4.2 THE OBJECTIVES AND SETUP OF EXPERIMENTS

There are two objectives of the experiments.

- To validate the speed and position performance with conventional optical rotary encoder.
- To apply the developed image rotary encoder as an absolute PID DC motor position control.

The experiment setup used for the developed image rotary encoder is shown in Figure 4.1. It includes control and instrumentation from NI ELVIS II board, two personal computers and hardware components. NI ELVIS II board is used to collect and control the physical data through the digital input-output, digital-to-analogue channel and analogue-to-digital channel. Hardware platform is the developed image rotary encoder coupled to the DC motor and conventional optical rotary encoder. Personal Computer I is used for the image processing algorithm to convert the captured image to the absolute position output. Personal Computer II is used to host LabVIEW software.

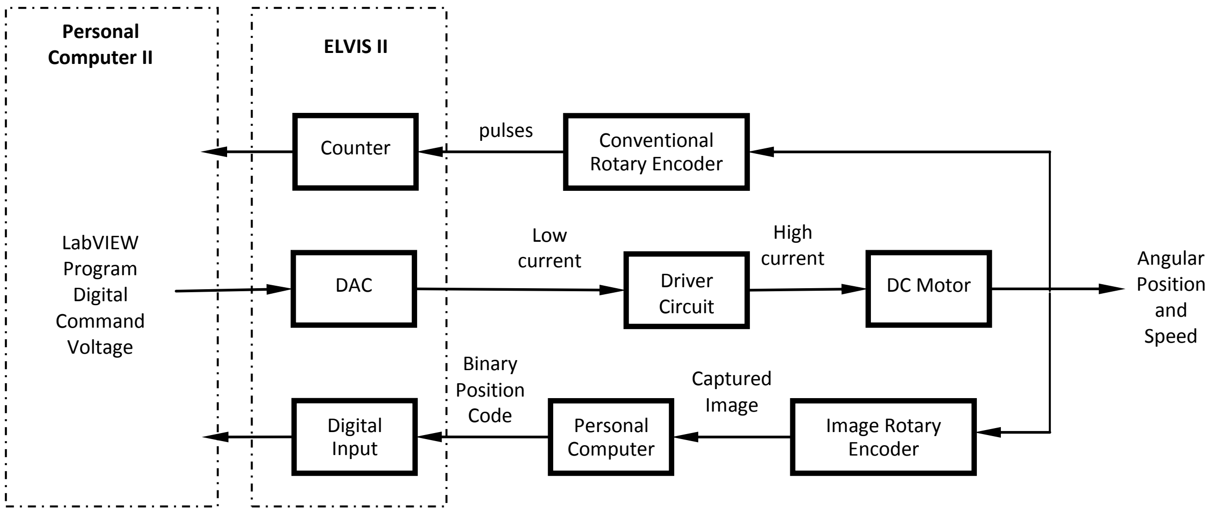


Figure 4.1: Experiment setup of the image rotary encoder for the experiment

The conventional rotary encoder used in the experiment is B106 optical rotary encoder from ESB Electronics Industries. Detailed specifications for the encoder are given in Table 4.1.

Table 4.1: B106 Optical rotary encoder specification

Technical specification	Value
Supply voltage	DC +5V ~ 24V
Output voltage	High voltage = > 85% Vcc Low voltage = < 0.3V Vcc
Resolution	500 pulses per revolution
Current requirements	≤ 120mA
Respond frequency	0 ~ 100 kHz
Output waveforms	Square wave

The analog output channel (DAC) does not produce enough power to drive the DC motor. A driver circuit (power transistor amplifier) is added between the DAC and the DC motor in order to increase the current to drive the DC motor. The circuit used to amplify the current is shown in Figure 4.2.

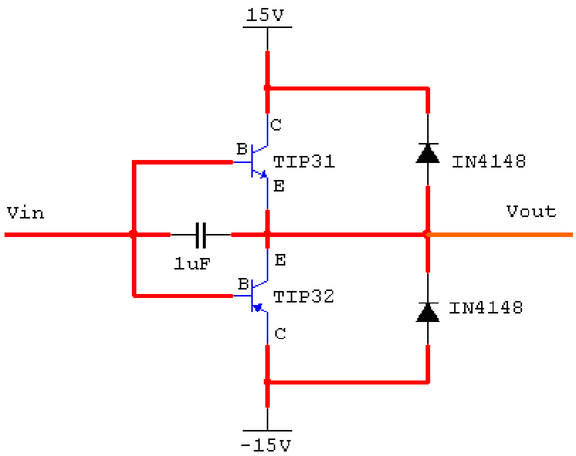


Figure 4.2: Amplifier circuit for the physical experiment

Source: Altaf, 2007

The amplifier used is a multi-directional amplifier – able to amplify both positive and negative voltage. The amplifier used TIP31 and TIP32 transistors, diode IN4148 and 1µF capacitor. With 15V and -15V power source, the amplifier can amplify current up to one ampere.

National Instruments product, NI ELVIS II, is used as the controller for the physical experiment and the program is written using LabVIEW Version 8.3. Laboratory virtual instrument engineering workbench, LabVIEW, is a graphical programming language. It uses icons to create applications whereby it resembles a flowchart. NI ELVIS II has eight channel analog inputs, two channel analog outputs, 24 digital inputs outputs, two counters, one frequency generator, digital multi-meter, one function generator, two input modulation and two channel oscilloscopes. NI ELVIS II uses a high speed USB to communicate with a personal computer. For the experiment, 10 digital inputs, one analog output and two channel counters are used. The digital input channel is used to read the binary position code from the image rotary encoder. The analogue output is used to drive the motor. The counter channel is used to read the conventional optical rotary encoder for data validation. NI ELVIS II board is shown in Figure 4.3.

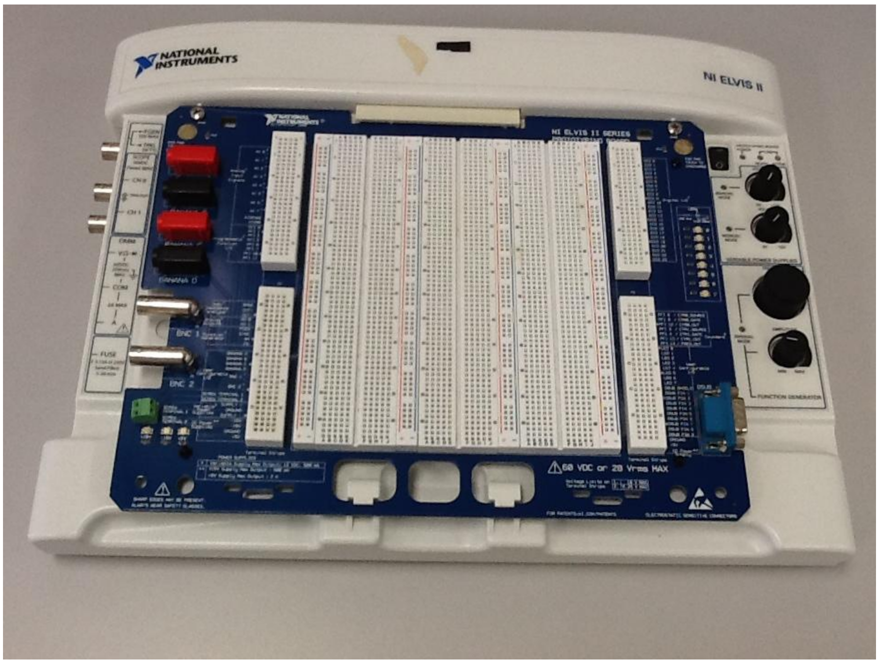


Figure 4.3: National Instruments Platform: NI ELVIS II

DC motor can be controlled by two methods which are: analogue drive or pulse-width modulation drive. In the experiment, analog drive is used to control the motor. The DC motor used in the experiment is SPG30-300K Cytron DC motor. It is equipped with a gearbox. Detailed specifications for the DC motor are presented in Table 4.2.

Table 4.2: SPG30-300K Cytron DC motor specification

Motor specification	Unit	Value
Nominal input voltage	Volt	12
Output power	Watt	1.1
Gear ratio		300 : 1
Nominal rated speed	RPM	12
Rated torque	mN.m	1176
Rated current	mA	410

4.3 IMAGE PROCESSING TIME

The performance of the developed image rotary encoder is analysed based on several characteristics which are: processing times, speed and position validation.

Processing time, T_{pt} , is the time it takes to complete an algorithm cycle. It measures the time from capturing the image, process it through algorithm and produce the output data. Using the Webcam C210 Logitech camera and a personal computer DELL with Intel (R) Pentium (R) Dual CPU E2160 @ 1.80 GHz Processor, the image rotary encoder for the system is limited to 30 frames per sec which is equivalent to 0.0333 sec per frame. After running for 5000 cycles, the average processing time for the system is 0.1345 sec. The average time is measured based on time to process the image from one frame to another as shown in Figure 4.4.

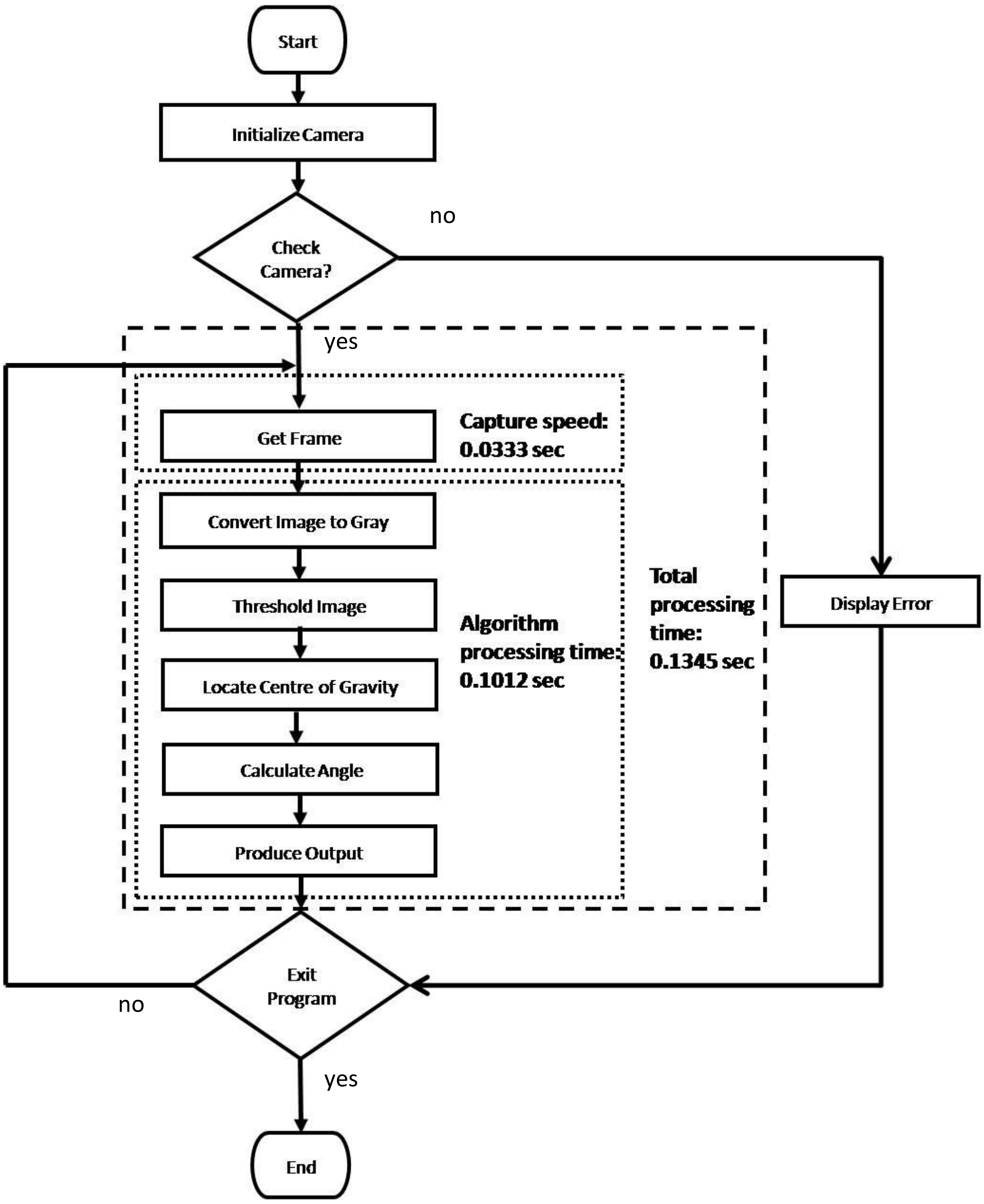


Figure 4.4: Algorithm processing time

The processing time affects the maximum speed that can be achieved by the system. The maximum speed $\omega_{\max}$ of the system is the maximum rotations (revolutions) per minute. The formula to calculate the speed is given by Equation 4.1.

$$\omega_{\max} = \frac{60}{T_{pt}} \tag{4.1}$$

Using the average processing time, the maximum speed for the system is 446 RPM. The speed is also limited by the DC motor used in the experiment. The speed of the motor is in the range of 0 to 28 RPM from the supply of 0 to 18 volts. To increase the speed, high speed camera and faster motor should be used.

4.4 PERFORMANCE VALIDATION WITH CONVENTIONAL INCREMENTAL ROTARY ENCODER

The performance of the image rotary encoder needs to be validated in term of its functionality and characteristics. The validation is done by comparing to the conventional incremental rotary encoder. Experiments are conducted for the speed and position validation with the conventional incremental rotary encoder.

4.4.1 Position Validation

Performance of the developed image rotary encoder in term of position is validated by comparing the angle from the developed image rotary encoder and the angle from conventional incremental rotary encoder. The correlation is presented in Figure 4.5.

The data is collected at the speed of 1.8 RPM. It is a slowest speed of the motor that can be achieved. Captured data from the developed image rotary encoder is in a binary position code with a 1024 absolute position. The data is converted to angle by using a look-up table. Every increment of binary position code represents 0.3516 degree (1024 binary positioning code for 360 degree). Thus, for example, 30 degree is represented by 85 binary position code.

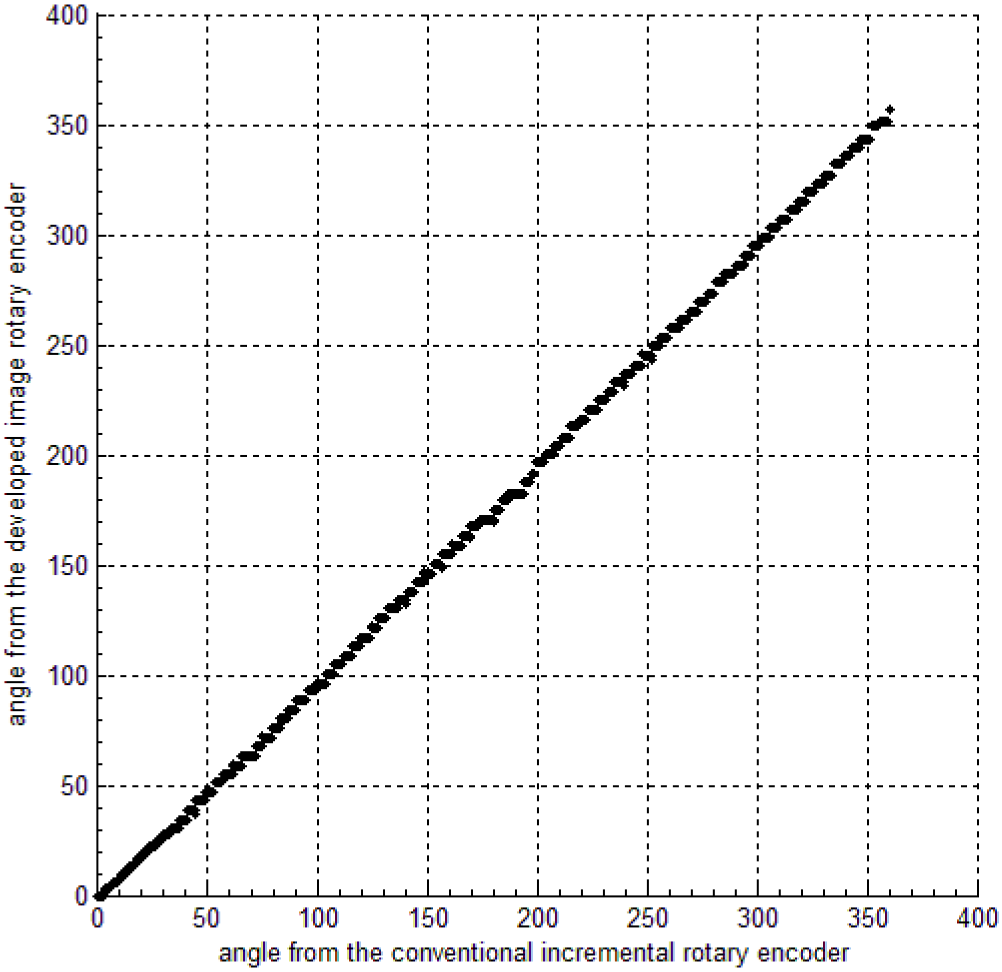


Figure 4.5: Plot for position validation

On the other hand, the conventional rotary encoder is in the form of pulses. The data is collected in the pulse counter and converted to angle by knowing the number of pulses. There are 500 pulses for each revolution of the conventional rotary encoder. Thus, 30 degree is equivalent to 56 pulses.

Based on the correlation in Figure 4.5, the angle given by the developed image rotary encoder is directly proportional to the conventional rotary encoder. The gradient (slope) of the linear regression line is 0.995 with a correlation coefficient, *r* of the data is 0.999.

4.4.2 Speed Validation

The experiment for the developed image rotary encoder was conducted with variable speeds. Without exceeding the maximum speed, the speed depends on the supply voltage to the DC motor. The speed affects the gap size of the developed image rotary encoder. The gap size is the gap between the binary position code on each data cycle output. The gap size is taken by the average data for 1000 cycle. The resultant data are shown in Table 4.3.

Table 4.3: Data taken for the speed validation

Supply voltage (Volt)	**Binary position code gap size from the developed image rotary encoder (BPC gap)**	**Speed from the developed image rotary encoder (RPM)**	**Pulse count from the conventional rotary encoder (pulses / sec)**	**Speed from the conventional rotary encoder (RPM)**	**Percentage difference (%)**
1.5	4	1.6	15	1.8	11.11
2	6	2.4	21	2.52	4.76
3.5	11	4.8	39	4.68	2.56
5	16	7	58	6.96	0.57
6.5	21	9.1	76	9.12	0.22
8	28	12.2	95	11.4	7.02
9.5	33	14.2	112	13.44	5.65
11	37	15.9	130	15.6	1.92
12.5	42	18.3	149	17.88	2.35
14	50	21.8	168	20.16	8.13
15	56	24.2	183	21.96	10.2
18	65	28.5	220	26.4	7.95

Captured data from the developed image rotary encoder is in a binary position code with a 1024 absolute position. The data is converted to speed by determining the average gap sized. The average gap size is divided by the quantity of the binary position code per revolution (1024 binary positioning code for 360 degree) to get the ratio per revolution. The data is then divided by the processing time, T_p to get the speed per sec. In order to get the speed in terms of revolution per minute, the speed per sec is multiply with 60 (1 minute equivalent to 60 sec). Thus, for example, 4 gap size is represented by 1.74 RPM. On the other hand, the conventional rotary encoder is in the form of pulses. The data is collected in the pulse counter and converted to speed by knowing the number of pulses per minutes. There are 500 pulses for each revolution of the conventional rotary encoder. Thus, 900 pulses is equivalent to 1.8 RPM. The resultant data are shown in Figure 4.6.

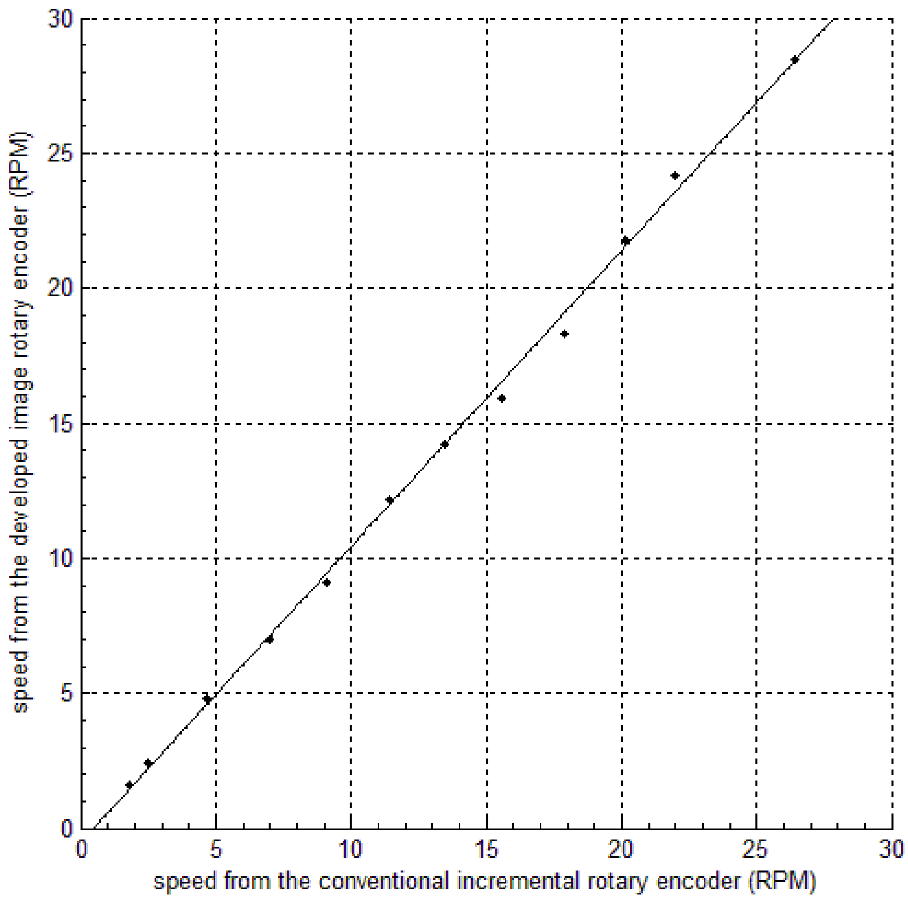


Figure 4.6: Plot for speed validation

Based on the correlation in Figure 4.6, the speed by the developed image rotary encoder is directly proportional to the conventional rotary encoder. The gradient (slope) of the linear regression line is 1.096 with a correlation coefficient, r of the data is 0.999.

Sample pictures are taken with several of speed as shown in Figure 4.7. Based on the Figure 4.7 (a-d), length of echo stream of light is increased with the speed of rotation. The echo stream is filter during the image processing stage by using a threshold method. The most bright spot is selected for the centre of gravity algorithm.

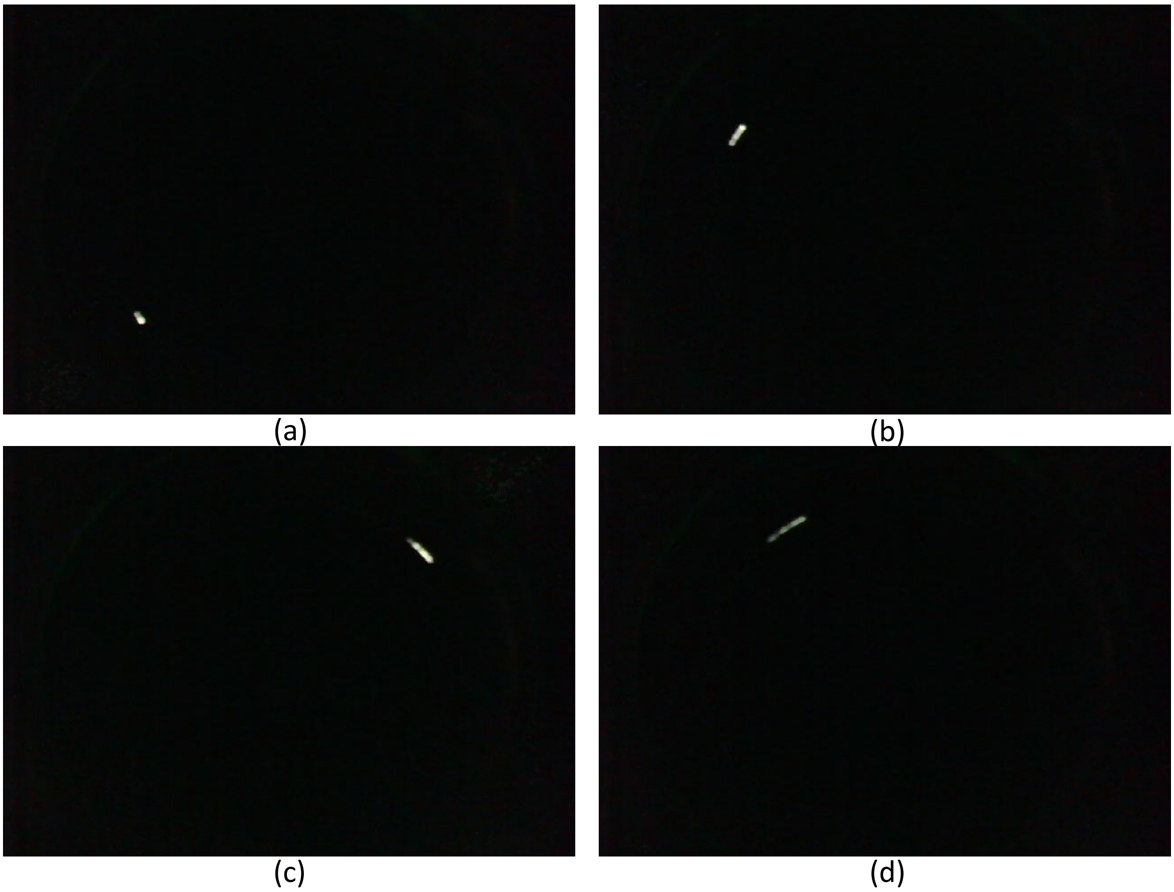
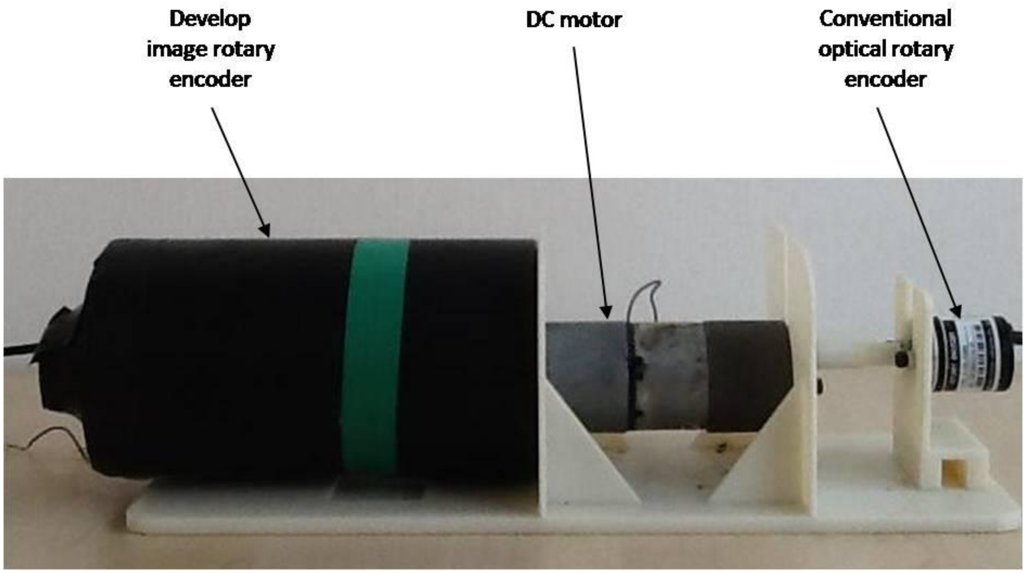


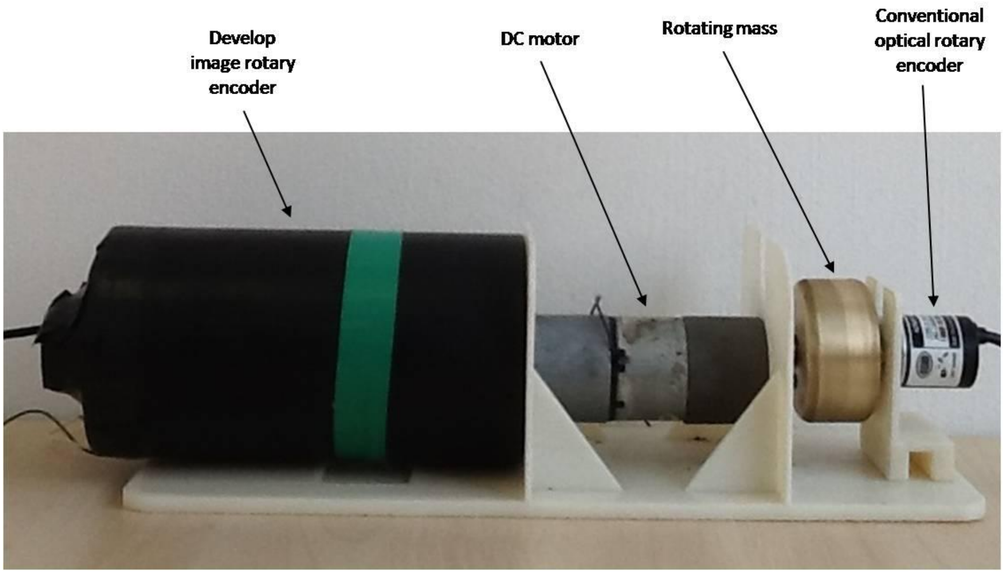
Figure 4.7: Sample images with several of speed (a) 4.68 RPM (b) 9.12 RPM (c) 13.44 RPM (d) 17.88 RPM

4.5 DC MOTOR PID POSITION CONTROL USING THE DEVELOPED IMAGE ROTARY ENCODER AS FEEDBACK

To test the system, the developed image rotary encoder was implemented in a DC motor PID position control. The experiment hardware is shown in Figure 4.8.



(a)



(b)

Figure 4.8: Experiment hardware setup (a) without load (b) with load

The experiment hardware combines the develop image rotary encoder with a DC motor and the shaft is coupled to a conventional optical rotary encoder. The experiments were conducted for two cases; with and without a rotating mass. The block diagram for the physical experiments is presented in Figure 4.9 while the LabVIEW Block Diagram is shown in Appendix C.

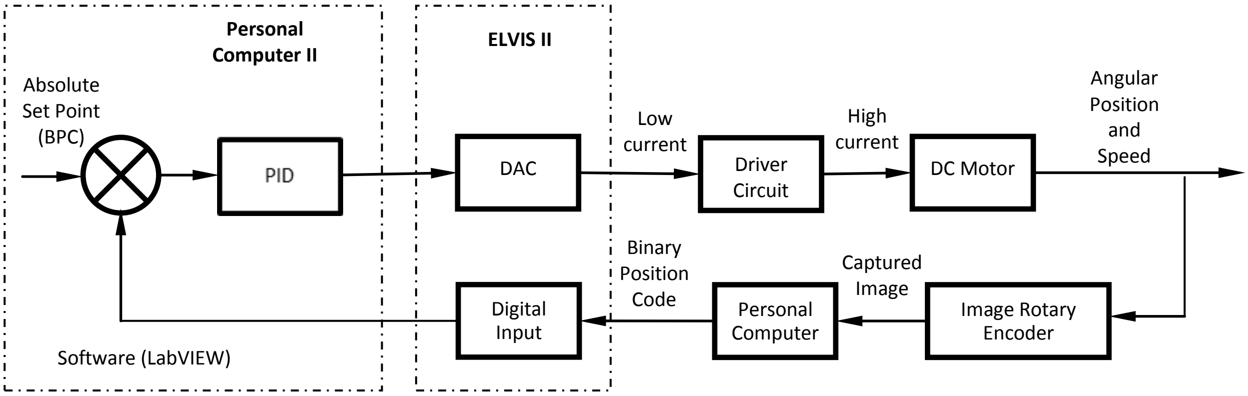


Figure 4.9: Block diagram for physical experiment of DC motor position control

4.5.1 Set Point

The controlled variable for the closed loop system of the DC motor position control is the absolute position code of the image rotary encoder. Resolution of the image rotary encoder is 1024 per revolution and is represented by a 10-bit digital number. The set point is based on the absolute position or binary position code.

4.5.2 Proportional, Integral and Derivative, (PID) Control

Controller for the system is a PID feedback control. It is a combination of proportional, integral and derivative control. The main control of the system is proportional control (K_p). It applies corrective force to the motor by increasing or reducing analog output to the motor proportional to the amount of error from the recent value to the set point value. Integral (K_i) and derivative controls (K_d) are added to eliminate steady-state error and reduce overshoot. The response of the PID can be described by Equation 4.2.

$$Output_{PID} = K_P E + K_i \sum (E\Delta t) + K_d \frac{\Delta E}{\Delta t} \tag{4.2}$$

Based on the Equation 4.2, the parameters for the PID controller need to be tuned. Parameter values are determined by using Ziegler-Nichols method (Kilian, 2006). Ziegler-Nichols is a classical method to tune parameters for PID controller. The steps to tune the parameters are:

1. Values for K_i and K_d are set to zero. Value for K_p are increased until output develops sustained oscillations (Figure 4.10)
2. At this instance, $K_p$the value is used as K_{pu} value. In our case, the K_{pu} value is 0.25.
3. Period of time, T_u is then measured. In our case, T_u is 1.9 sec.
4. Based on the K_{pu} and T_u values, tuning parameters for K_p , K_i and K_d can be calculated and are given in Table 4.4.

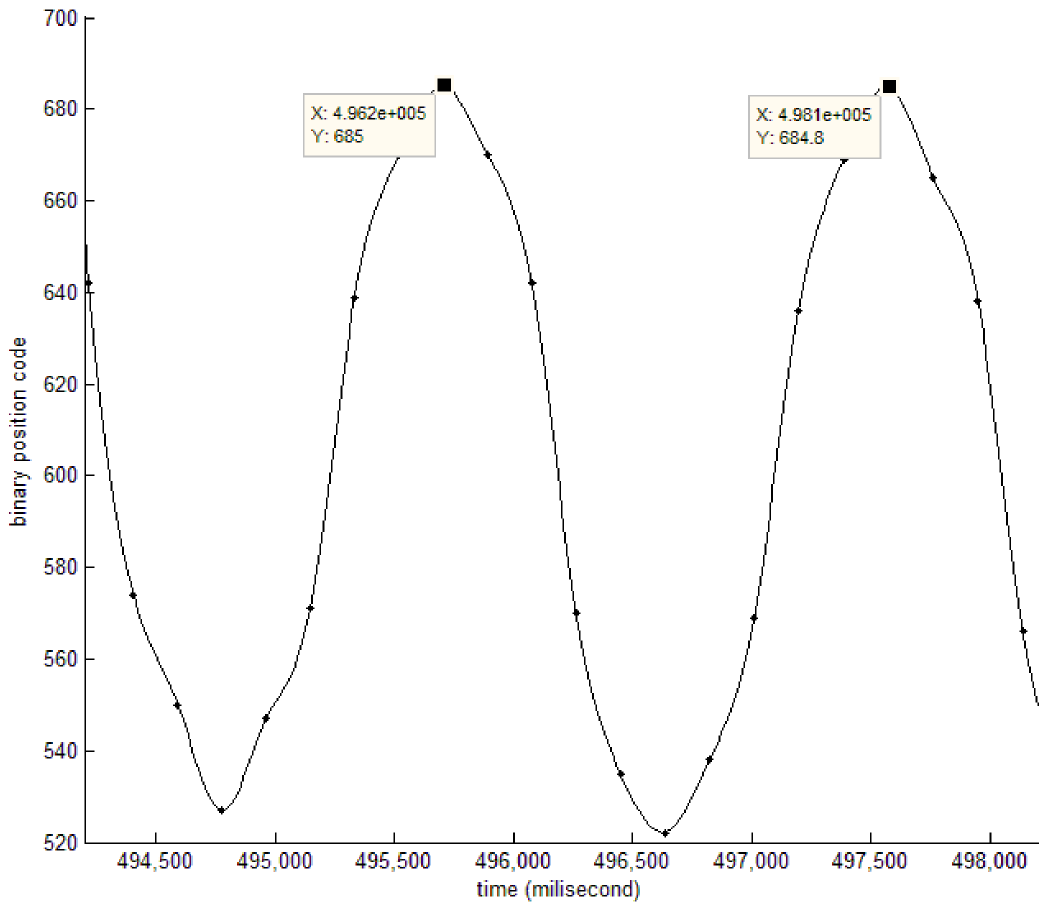


Figure 4.10: Response of the DC motor position at constant amplitude by the $K_p$tuning

Table 4.4: Tuning parameter for PID controller using Ziegler-Nichols method

Parameter	K_p	K_i	K_d
ZN PID formula	$0.6K_{pu}$	$T_u/2$	$T_u/8$
Actual PID values	0.15	0.95	0.2375

4.5.3 Performance for PID Position Control

Performance for the PID position control is based on tuning parameters by the Ziegler-Nichols method. Two types of experiments were carried out for the time response: one experiment without rotating mass and six experiments with rotating mass at different set points. From the step response plot, the system is found to be an under-damped second order system. The under-damped second order system can be studied from Figure 4.12 (Nise, 2004).

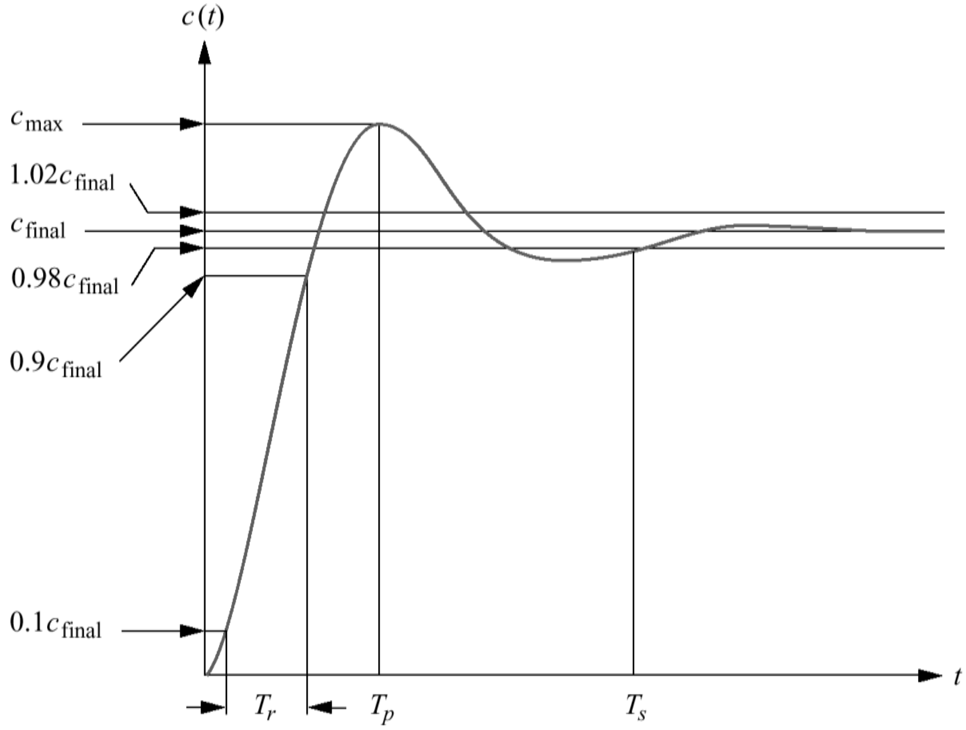


Figure 4.11: Second order under-damped response specifications

Source: Nise (2004)

Based on the Figure 4.11, second order under-damped response specifications can be defined as below:

1. Rise time, T_r. Time required for the waveform to go from 0.1 of the final value to 0.9 of the final value.
2. Peak time, T_p. Time required by the system to reach the maximum peak.
3. Percent overshoot, $\%OS$. Percentage the waveform overshoots the steady state, value at the peak time.
4. Settling time, T_s. Time required for the transient's damped oscillation to reach and stay within $\pm 2\%$ of the steady state value.
5. Percentage steady state error is the percentage of deviation between the set point and the final value of the response.

Figure 4.12 to Figure 4.18 show the full plot response of the physical experiment.

- Figure 4.12– Time response for set point 600 binary position code without mass
- Figure 4.13 – Time response for set point 150 binary position code with mass
- Figure 4.14 – Time response for set point 300 binary position code with mass
- Figure 4.15 – Time response for set point 450 binary position code with mass
- Figure 4.16 – Time response for set point 600 binary position code with mass
- Figure 4.17 – Time response for set point 750 binary position code with mass
- Figure 4.18 – Time response for set point 900 binary position code with mass

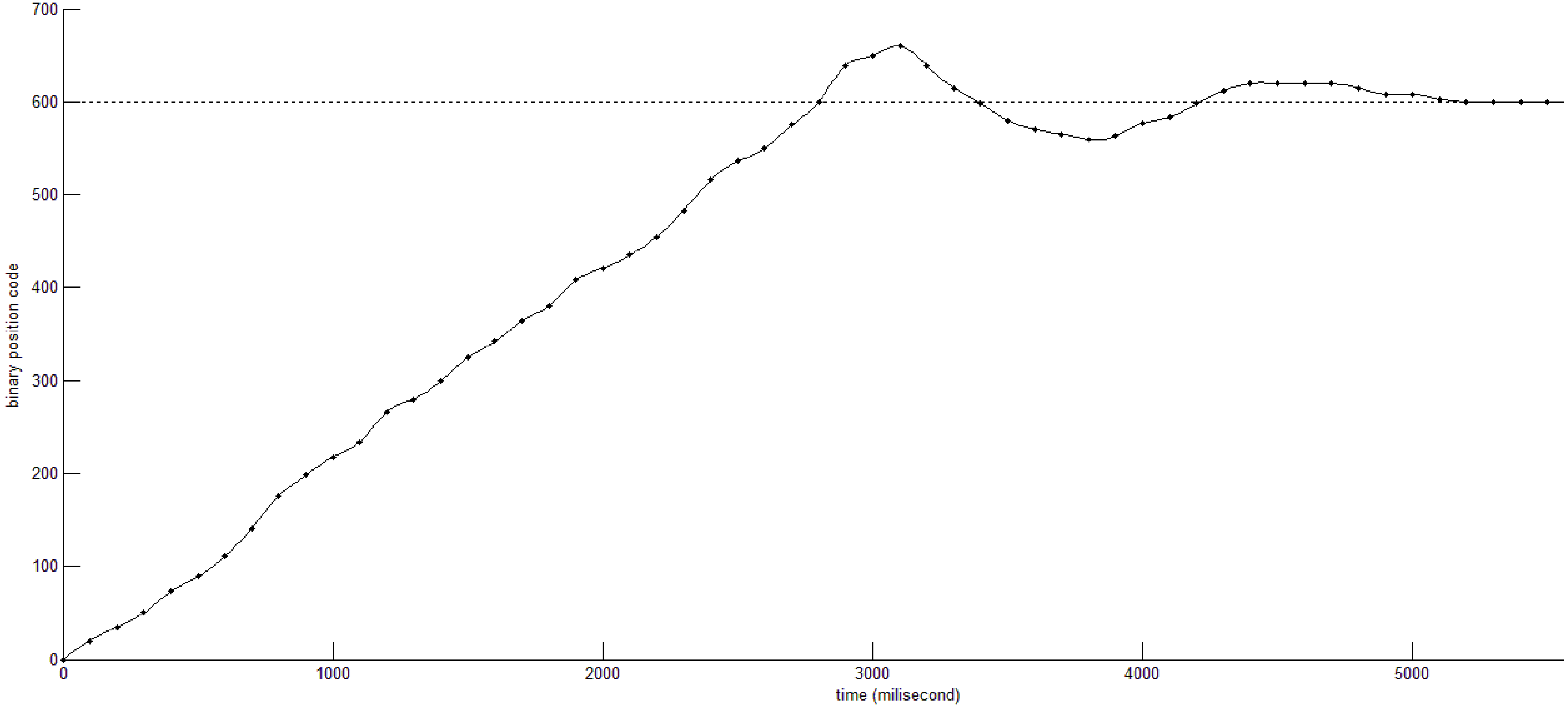


Figure 4.12: Step response of the physical experiment for the DC motor PID position control – 600 Set points and without mass

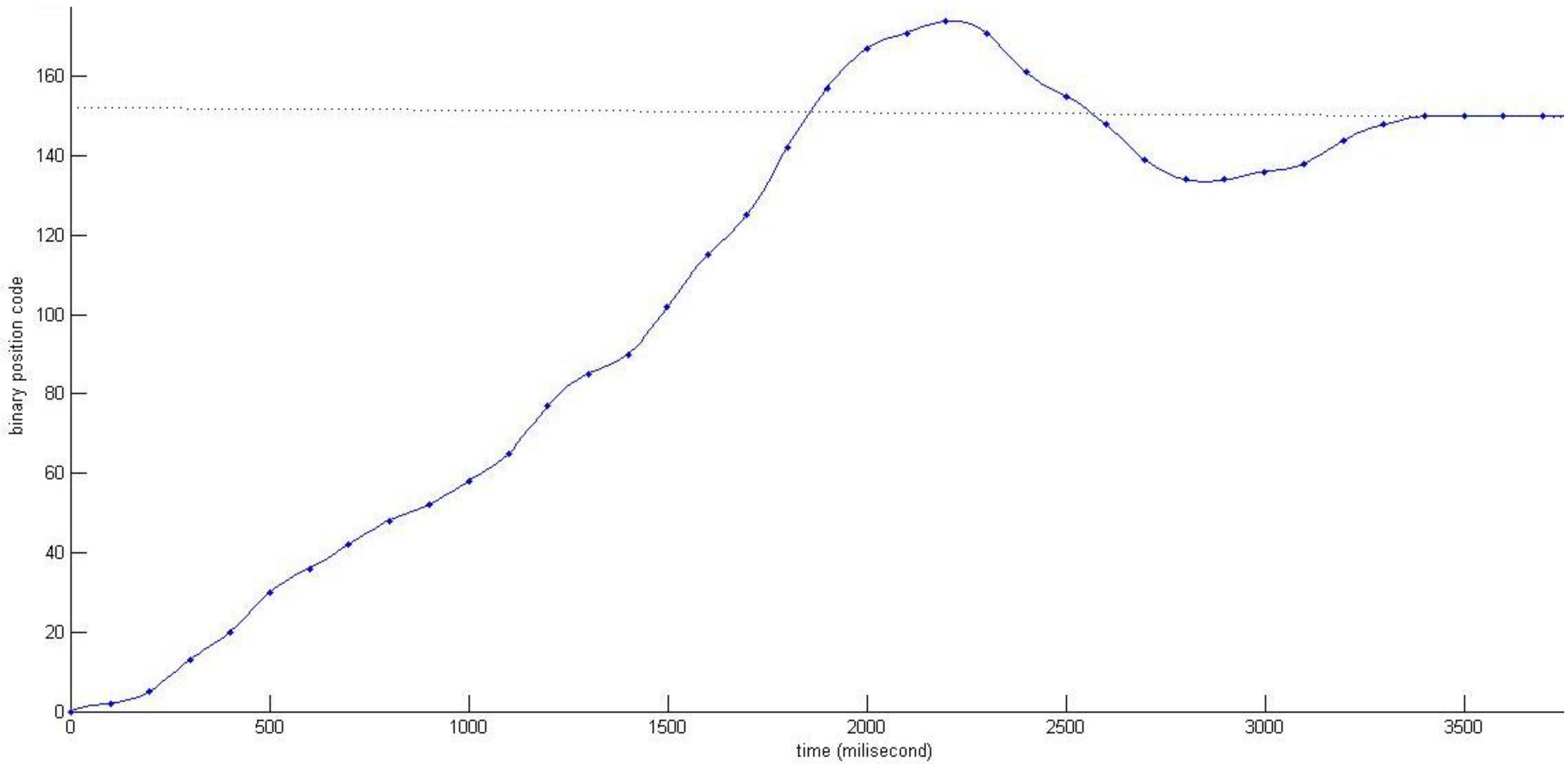


Figure 4.13: Step response of the physical experiment for the DC motor PID position control – 150 Set points and with mass

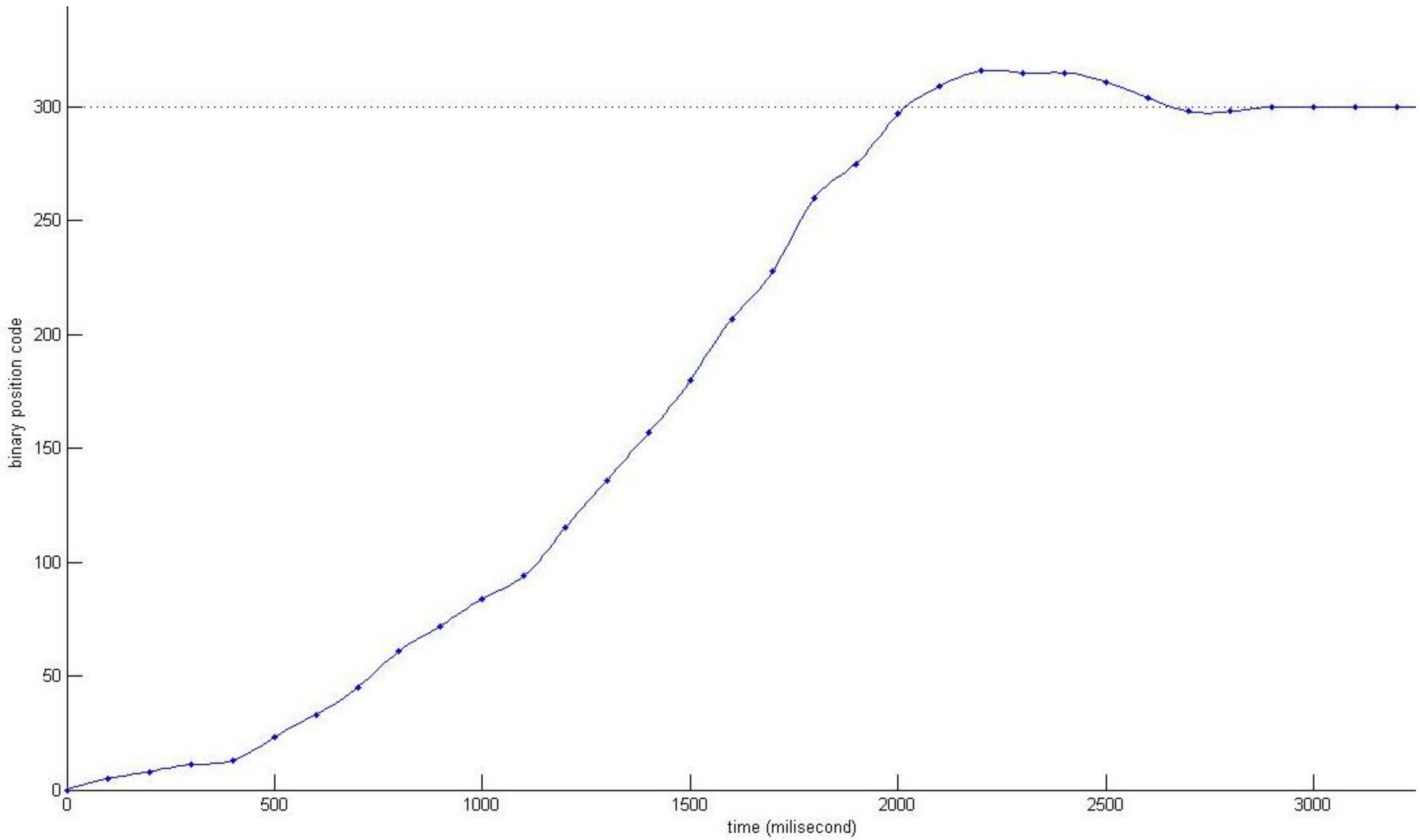


Figure 4.14: Step response of the physical experiment for the DC motor PID position control – 300 Set points and with mass

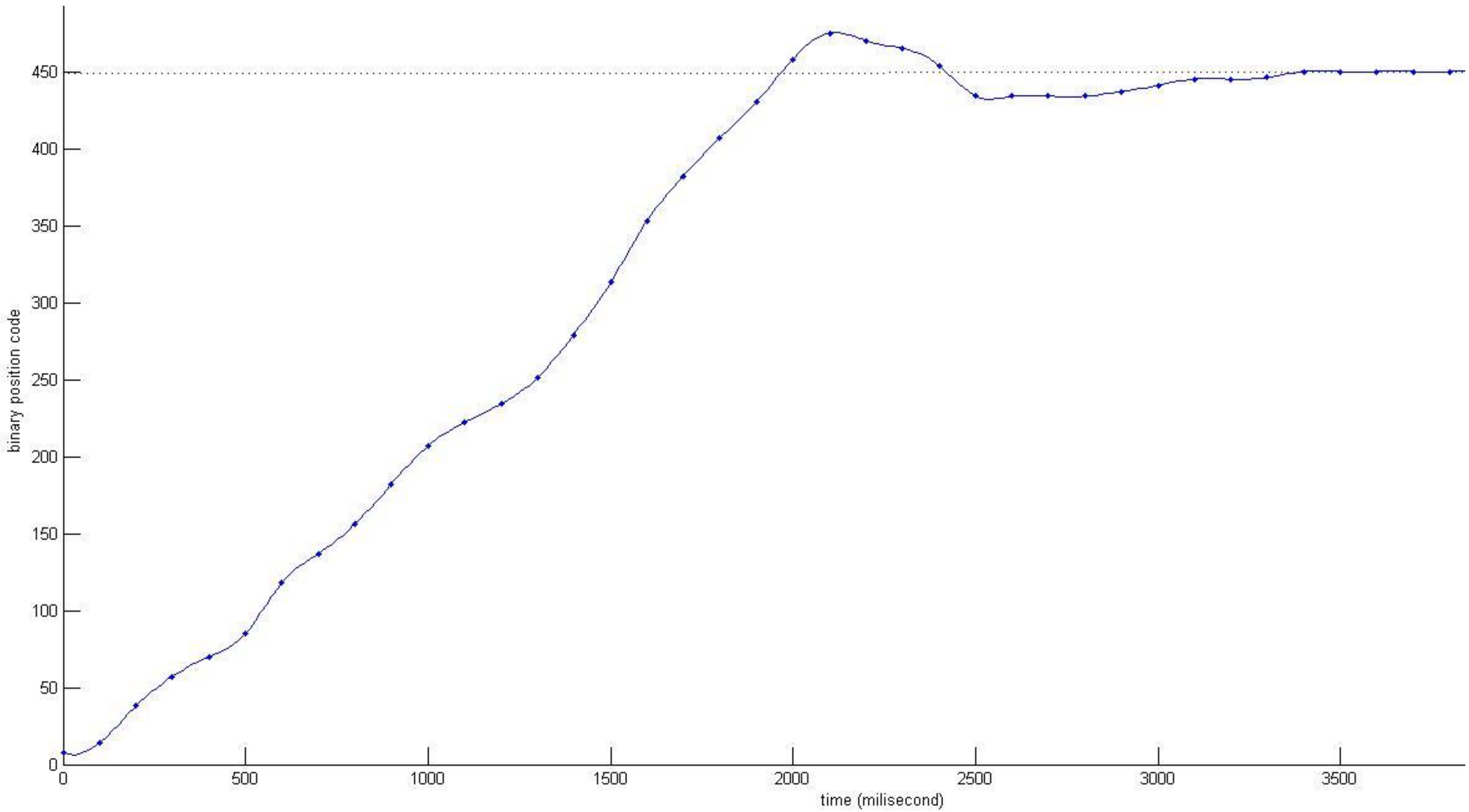


Figure 4.15: Step response of the physical experiment for the DC motor PID position control – 450 Set points and with mass

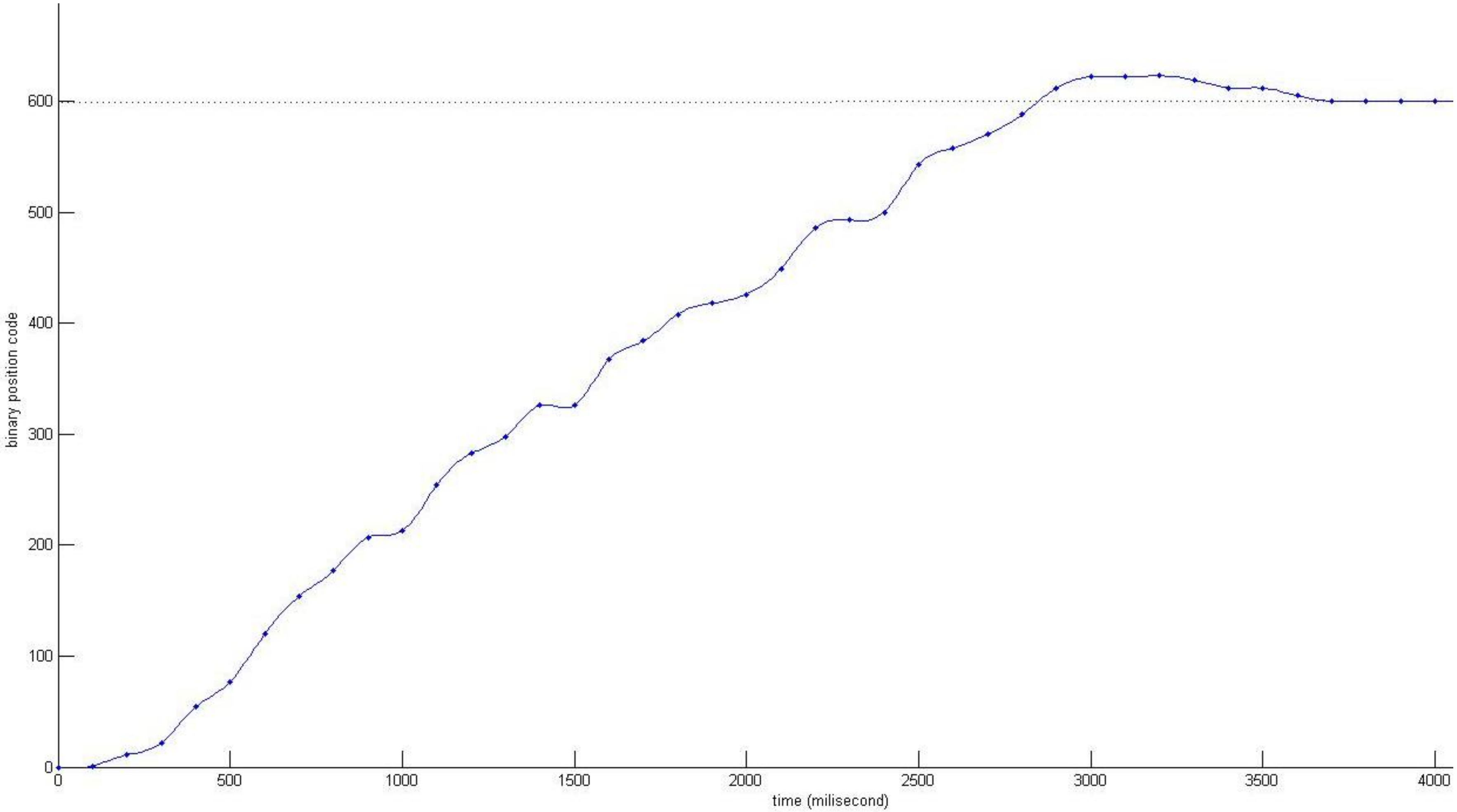


Figure 4.16: Step response of the physical experiment for the DC motor PID position control – 600 Set points and with mass

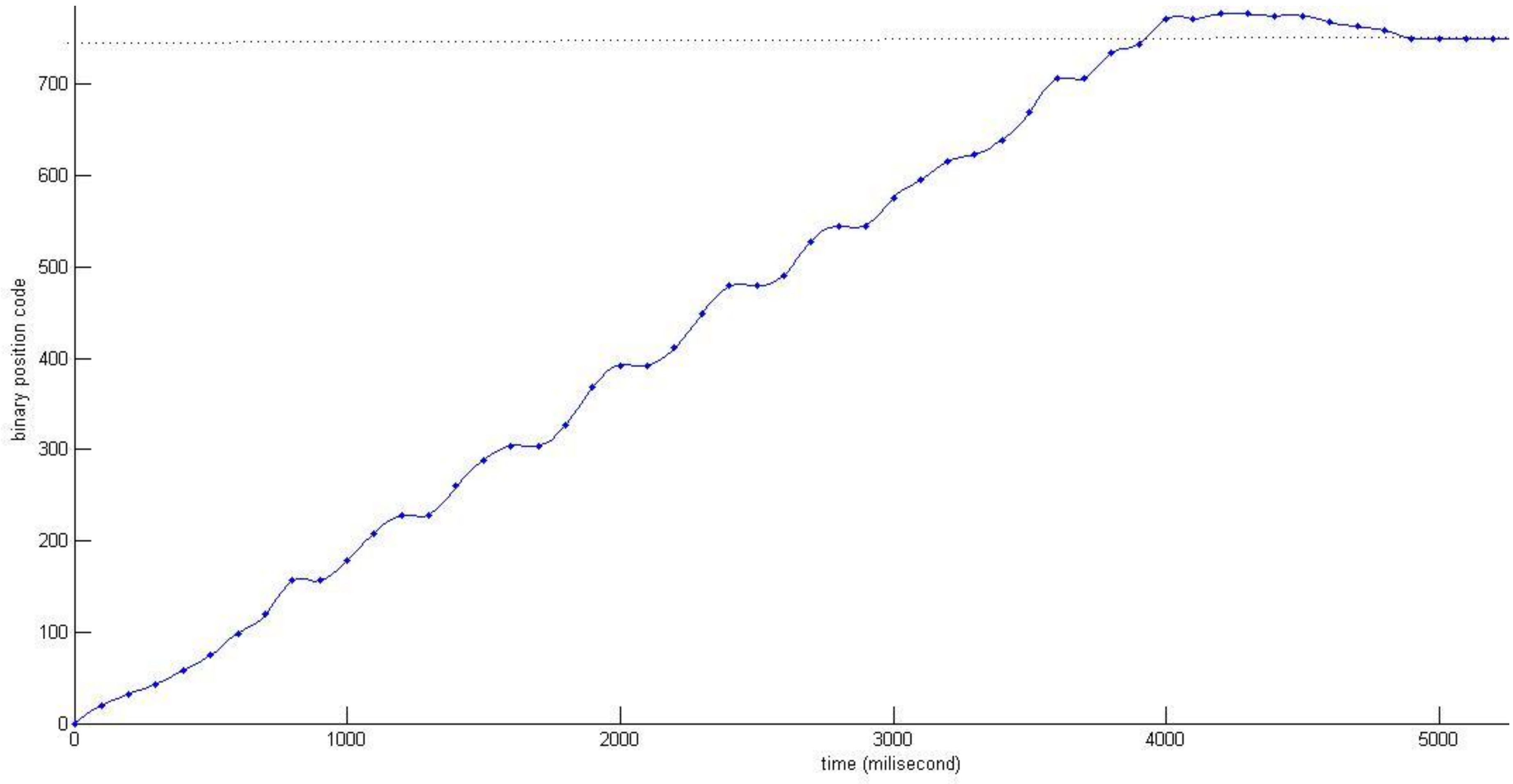


Figure 4.17: Step response of the physical experiment for the DC motor PID position control – 750 Set points and with mass

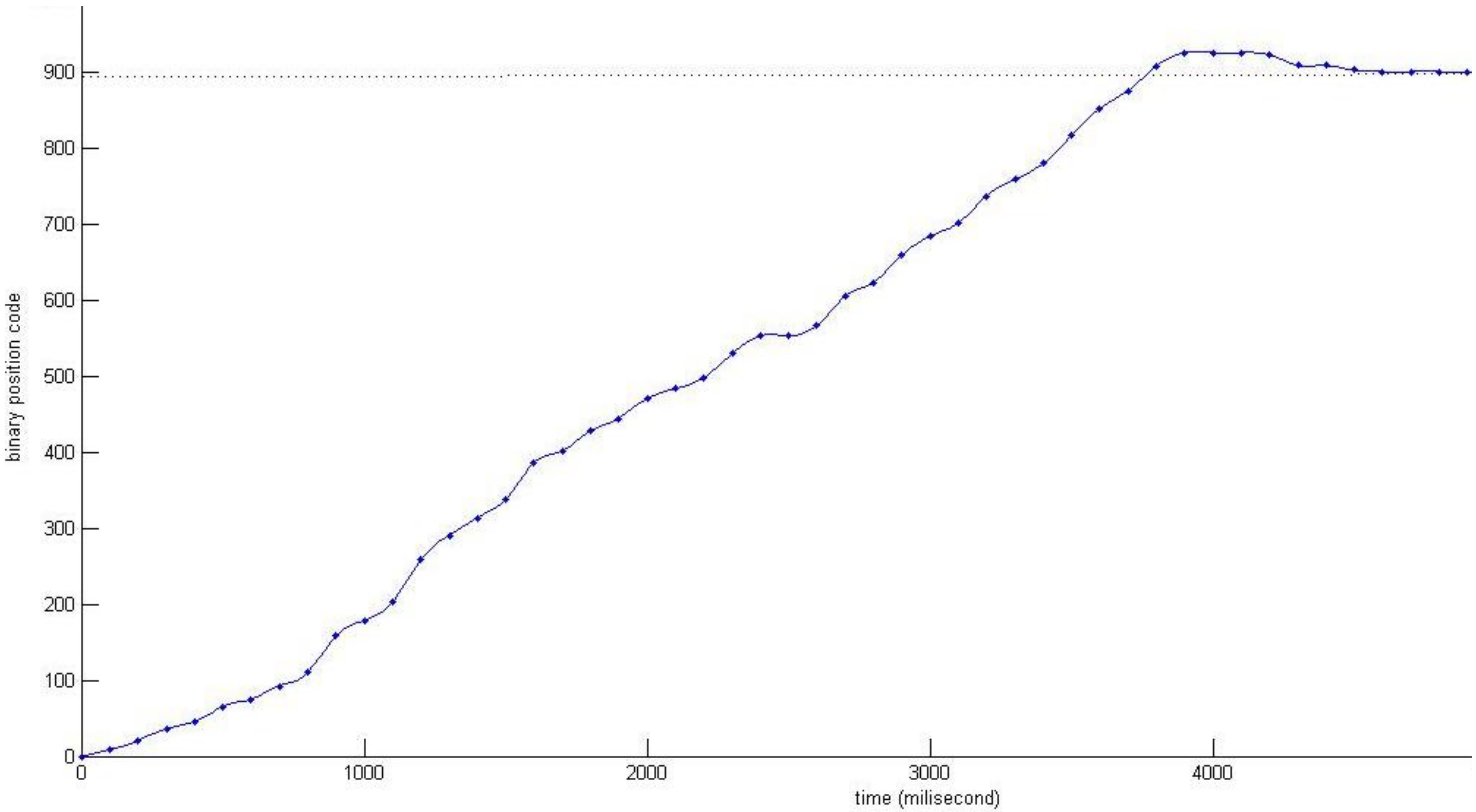


Figure 4.18: Step response of the physical experiment for the DC motor PID position control – 900 Set points and with mass

Table 4.5 below summarizes the results of the step response for the physical experiments with rotating mass and without rotating mass.

Table 4.5: Step response results

Set point (BPC)	**Rise time, T_r (sec)**	**Peak time, T_p (sec)**	**Percent overshoot, (%)**	**Settling time, T_s (sec)**	**Steady State Error (%)**
600 (without mass)	2.285	3.100	10	4.800	0%
150	1.471	2.200	16	3.400	0%
300	1.319	2.200	5.3	2.900	0%
450	1.554	2.100	5.6	3.400	0%
600	2.042	3.201	3.8	3.701	0%
750	3.026	4.199	3.6	4.899	0%
900	2.789	3.900	2.8	4.600	0%

Based on the result from Table 4.5, the developed image rotary encoder can be applied as position feedback device in motor control with no steady state error.

4.6 SUMMARY

Physical experiments confirmed that the develop image rotary encoder is functioning as good as the conventional rotary encoder.

- Figure 4.6 plot indicated that the speed measurement from the developed image rotary encoder is directly proportional to the speed measurement from the conventional rotary encoder with a 0.999 correlation coefficient.
- Figure 4.5 plot indicated that position measurement from the developed image rotary encoder is directly proportional to the position measurement from the conventional rotary encoder a 0.999 correlation coefficient.
- The developed rotary encoder is an absolute rotary encoder.
- Although the gap size between binary position code for the image rotary encoder is affected by the speed of the DC motor, the image rotary encoder can be applied for position control. The developed image rotary encoder is an effective feedback device for the PID DC position motor control with zero steady state error for several set points.

In the next chapter, research summary and recommendations for future works will be presented.

CHAPTER 5

RESEARCH CONCLUSION

5.1 RESEARCH SUMMARY AND CONCLUSION

The limitation of conventional rotary encoder in terms of performance, manufacturing difficulties and cost motivated the research to come out with an alternative solution. Thus, the purpose of this research is to develop an absolute rotary encoder using an image sensor as a sensing element and an image processing technique to translate the rotational movement to a position feedback device. This research proposed a webcam as a sensing element and an OpenCV programming platform to process the algorithm that is specifically designed to captured the images and then to convert them into motion data. The research proposed a much simpler method in developing the code disc compared to the conventional incremental or absolute rotary encoder that requires complicated steps in manufacturing the code disc.

The conclusions of this research are stated below:

- In this study, with the image processing technique, image from sensing element can be converted into motion data. The motion data for this study is in binary position code similar to conventional absolute rotary encoder.

- In this study, results from physical experiments comparing the developed image rotary encoder and conventional rotary encoder validated that the developed image rotary encoder can function as the conventional rotary encoder. This is indicated by the experiments setup that the speed measurement from the developed image rotary encoder is directly proportional to the speed measurement from the conventional rotary encoder and that the position measurement from the developed image rotary encoder is directly proportional to the position measurement from the conventional rotary encoder with a 0.999 correlation coefficient.

- Experimental results from chapter four confirmed that the developed image rotary encoder can be implemented as a feedback device to a DC motor PID position control. Binary position code can be utilized as the position set points to a DC motor.

5.2 RECOMMENDATIONS FOR FUTURE WORKS

The developed image rotary encoder can be studied further both to enhance the encoder performance as well as to use in different control applications. Below are recommendations for future studies on the developed image rotary encoder.

1. To increase the processing time efficiency by implementing parallel computing technique in processing the image data.
2. To increase the speed range by using high speed camera and faster motor.
3. To increase the position resolution by using high resolution camera.
4. To implement speed control using the gap size between the binary position code as the speed set point.
5. To implement other than PID control such as fuzzy logic control.
6. To become a feedback device for other than a DC motor.
7. To become an absolute linear image rotary encoder.

The results of this research hopefully can benefit other researchers and industries from various fields especially as an alternative feedback element in improving a motion control system.

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APPENDIX A

IMAGE PROCESSING MAIN PROGRAM

```
#include "open_cv.h"

int main( int argc, char **argv )
{

    open_lookup_table("lu8.dat");      // Step 01: Create look-up table
    CvCapture *capture = 0;              // Step 02: Initialize camera
    capture = cvCaptureFromCAM(-1);
    if (!capture)
    {
      fprintf(stderr, "!!! Cannot open initialize webcam!\n" );
      return -1;
    }
    // Step 03: Create a window for the video
    cvNamedWindow("result", CV_WINDOW_AUTOSIZE);
    //cvNamedWindow("thres", CV_WINDOW_AUTOSIZE);
    // New IplImage* to store the processed image
    IplImage* frame = 0;
    IplImage* gray_frame = 0;
    IplImage* thresh_frame = 0;
    IplImage* cog = 0;
    // Variables
    CvMoments moments;
    double m00, m10, m01;
    int center_x = 0;
    int center_y = 0;
    char key = 0;
    FILE *fpt2;
    fpt2 = fopen("xyc.dat", "w");

    HINSTANCE hLib;
    inpfuncPtr inp32;
    oupfuncPtr oup32;
    /* Load the library */
    hLib = LoadLibrary("inpout32.dll");
    inp32 = (inpfuncPtr) GetProcAddress(hLib, "Inp32");
    oup32 = (oupfuncPtr) GetProcAddress(hLib, "Out32");

    while (key != 27) // ESC
    {
        frame = cvQueryFrame(capture);
        if(!frame)
        {
            fprintf( stderr, "!!! cvQueryFrame failed!\n" );
            break;
        }
        gray_frame    =    cvCreateImage(cvSize(frame->width,    frame-
        >height), frame->depth, 1);
        if (!gray_frame)
        {
            fprintf(stderr, "!!! cvCreateImage failed!\n" );
```

```
        return 0;
    }
    thresh_frame     =     cvCreateImage(cvSize(gray_frame->width,
    gray_frame->height), gray_frame->depth, 1);//BUAT THRESHOLD
    if (!thresh_frame)
    {
        fprintf(stderr, "!!! cvCreateImage failed!\n" );
        return 0;
    }
    cog  =  cvCreateImage(cvSize(thresh_frame->width,  thresh_frame-
    >height), thresh_frame->depth, 1);
    if (!cog)
    {
        fprintf(stderr, "!!! cvCreateImage failed!\n" );
        return 0;
    }

    // create gray image
    BwImage  gray_frameA(gray_frame);
    RgbImage  frameA(frame);
    for(int i=0;i<frame->height;i++)
        for(int j=0;j<frame->width;j++)
            gray_frameA[i][j]=    (uchar)(frameA[i][j].b*0.114    +
            frameA[i][j].g*0.587 + frameA[i][j].r*0.299);

    //SET PARAMETER THRESHOLD
    cvThreshold(gray_frame,thresh_frame,200,255,CV_THRESH_BINARY);

    //cari cog
    cvMoments(thresh_frame, &moments, 0);
    m00 = cvGetSpatialMoment(&moments, 0,0);
    m10 = cvGetSpatialMoment(&moments, 1,0);
    m01 = cvGetSpatialMoment(&moments, 0,1);

    // TBD check that m00 != 0
    center_x = m10/m00;
    center_y = m01/m00;

    //print cog
    printf("%d,%d\n",center_x,center_y);

    int loc;
    loc = check_point(center_x,center_y);
    output_out(loc);

    // Release resources
    cvReleaseImage(&gray_frame);
    cvReleaseImage(&thresh_frame);
    cvReleaseImage(&cog);

  // Exit when user press ESC
    key = cvWaitKey(27);
}

/* Unload the library */
printf("Data Saved in Output.dat \n\n");

(oup32)(0xDD00,0);
(oup32)(0xDD02,3);
```

```
    FreeLibrary(hLib);

    // Free memory
    cvDestroyWindow("result");
    cvDestroyWindow("thres");
    cvReleaseCapture(&capture);
    fclose(fpt2);
    //fclose(fpt3);

    return 0;
}
```

APPENDIX B

SUB PROGRAM

```
#ifndef OPEN_CV_H_INCLUDED
#define OPEN_CV_H_INCLUDED

#include "cv.h"
#include "highgui.h"
#include <stdio.h>
#include <windows.h>
#include <stdbool.h>
#include "iocpp.h"
#include <math.h>

#define PI 3.14159265

//untuk image
typedef IplImage* (*callback_prototype)(IplImage*);

template<class T> class Image
{
  private:
    IplImage* imgp;
  public:
    Image(IplImage* img=0) {imgp=img;}
    ~Image(){imgp=0;}
    void operator=(IplImage* img) {imgp=img;}
    inline  T*  operator[](const  int  rowIndx)  {return  ((T  *)(imgp-
    >imageData + rowIndx*imgp->widthStep));}
};

typedef struct{
  unsigned char b,g,r;
} RgbPixel;

typedef struct{
    float b,g,r;
}RgbPixelFloat;

typedef Image<RgbPixel>       RgbImage;
typedef Image<RgbPixelFloat>  RgbImageFloat;
typedef Image<unsigned char>  BwImage;
typedef Image<float>          BwImageFloat;

//untuk parallel port
typedef short _stdcall (*inpfuncPtr)(short portaddr);
typedef void _stdcall (*oupfuncPtr)(short portaddr, short datum);

//setting para lut
const int num_of_point = 1468;
int x[num_of_point];
int y[num_of_point];
int c[num_of_point];
int point_database[num_of_point];
```

```
CPerfTimer masa; // nanti bleh buang

//para utk output
int output, output_a, output_b = 0;

void open_lookup_table(char filename[]);
int check_point(int center_x, int center_y);
void output_out(int loc);
void record_data_lut(int center_x, int center_y, FILE* fpt4);

void open_lookup_table(char filename[])
{

    FILE *fpt;
    fpt=fopen(filename, "r");
    for (int f=0; f < num_of_point ; ++f)
    {
        fscanf(fpt, "%d\t%d\t%d", &x[f], &y[f], &c[f]);
    }
    fclose(fpt);
    return;
}

int check_point(int center_x, int center_y)
{

    int output;
    float angle_a,angle;
    int c_x = 0;
    int c_y = 0;
    float N[1024];
    angle_a = ((atan2(center_y-c_y,center_x-c_x))*(180/PI));
    angle = 90 - angle_a;

    if (angle_a < 0)
    angle = 360 - angle_a + 90;

    if (angle >= N[0] && angle < N[1])
    output = 1;

    else if (angle >= N[1] && angle < N[2])
    output = 2;

    ...

    else if (angle >= N[1022] && angle < N[1023])
    output = 1023;

    else if (angle >= N[1023] && angle < N[0])
    output = 0;

    else
    printf("%salah\n");

    return output;

}

void output_out(int loc)
{
```

```
    output = loc;

    if (output < 256)
    {
        output_a = output;
        output_b = 3;
    }

    if (output > 255 && output < 512)
    {
        output_a = output - 256;
        output_b = 2;
    }

    if (output > 512 && output < 768)
    {
        output_a = output - 256;
        output_b = 1;
    }

    if (output >= 768)
    {
        output_a = output - 256;
        output_b = 0;
    }

    (oup32)(0xDD00,output_a);
    (oup32)(0xDD02,output_b);

    return;
}

void record_data_lut(int center_x, int center_y, FILE* fpt4)
{
    fprintf(fpt4,"%d %d\n",center_x,center_y);
    return;
}

#endif // OPEN_CV_H_INCLUDED
```

APPENDIX C

LABVIEW BLOCK DIAGRAM FOR PID