MOIRÉ METHOD BASED TILT SENSING SYSTEM FOR LANDSLIDES MONITORING USING RASPBERRY PI

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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ABSTRAK

Tanah runtuh boleh menyebabkan kerugian yang mengerikan seperti kehilangan nyawa, kemerosotan ekonomi, pengurangan infrastruktur, dan menjejas ekosistem sungai. Tujuan kajian ini adalah mengaji satu sistem penginderaan kecondongan untuk pemantauan tanah runtuh berasaskan teori corak moiré dengan menggunakan Raspberry Pi. Algoritma untuk mengesan sentri daripada corak moiré telah dikajikan. Kelebihan utama menggunakan teori corak moiré ialah ia dapat menunjukkan perubahan dalam corak walaupun mengalami anjakan yang kecil. Prototaip algoritma telah diuji dengan corak moiré yang dapatkan melalui simulasi untuk membuktikan kebolehkerjaan teori moment sebelum pemasangan sistem penginderaan kecondongan. Kesan jarak kerja kamera ke atas kualiti imej yang ditangkap dengan menggunakan Logitech HD Webcam C310 telah dikaji untuk menentukan jarak kerja kamera yang sesuai. Raspberry Pi telah disambungkan dengan 2 light-emitting diode (LED) yang berbeza warna sebagai isyarat. Keputusan yang diperolehi selepas algoritma digunakan ke atas corak moire yang dihasilkan, dan ia menunjukan algoritma berjaya mengesan sentri corak moire dan menilai koordinasi sentri tersebut. Beberapa penambahbaikan telah dicadangkan dalam laporan ini, untuk mendapatkan sistem pengindaraan kecondongan yang lebih baik dan mudah alih bagi tujuan pemantauan tanah runtuh.

ABSTRACT

Landslides may lead to appalling loss such as loss of life, economic decline, decimation of infrastructure, and impacts river ecosystems. The purpose of this research is to develop a tilt sensing device based on moiré fringe pattern theory for landslide monitoring using Raspberry Pi. An algorithm to detect the centroid of the moiré fringe pattern was developed. The main advantage of using moiré fringe pattern theory is it able to show changes in pattern even it experienced tiny displacement. The prototype algorithm was tested with simulated moiré fringe pattern to prove workability of moment theory before fabricating the tilt sensing device. The effect of camera working distance onto the quality of image captured by using Logitech HD Webcam C310 was studied to determine the suitable camera working distance. The Raspberry Pi was connected with 2 different colour of light-emitting diodes (LED) to show to signal as the output. The results obtained after the centroid detection algorithm applied moiré fringe patterns produced, and it showed the algorithm manage to detect the centroid of the moiré fringe patterns and its coordinate value. Some potential improvements are suggested in this report which can be made to achieve a better and portable tilt sensing device for landslide monitoring.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.0 Overview

In this chapter, the following topics regarding the introduction are discussed. First of all, the brief background of the landslide is presented and the project outline is discussed.

1.1 Research Background

A landslide is the movement of rock, earth or debris down a sloped section of land. Landslides are a type of “mass wasting”, which denotes any down-slope movement of soil and rock under the direct influence of gravity. Although Malaysia is not a precipitous country (mountains and hills are less than 25% of the terrain), slope failures/landslides are a frequently happened. From 1993-2011, around 28 major landslides were reported in Malaysia with a total loss of more than 100 lives. Moreover, from 1973-2007, the total economic loss due to landslides in Malaysia was estimated about US $1 billion. Collapsed of the 14-storey block A of the Highland Tower in Ulu Klang, Selangor was the most tragic landslide in Malaysia with 48 deaths. (Rahmana & Mapjabilb, 2017) To prevent the landslide happens suddenly and lead to more tragedies, a monitoring system onto the landslide should be developed. However, almost every landslide has multiple causes. Therefore, detecting and monitoring the landslide in the aspect of slope movement is a more suitable method instead of monitoring the sources of the causes.

Tiltmeter are used extensively in detecting the ground movement. Tiltmeter is a sensitive inclinometer designed to measure very small changes from the vertical level. A sensitive tiltmeter can detect changes of as little as one arc second. However, the tiltmeter can only detect the changes in single plane of movement. In order to detect in both vertical and horizontal axes, two tiltmeter are required.

Detecting ground motion by using satellite radar interferometry has been used for decades. The technology used is interferometric synthetic aperture radar (InSAR) analysis. This analysis calculates the change in distance from the satellite to each ground pixel based on the change in phase of the reflected radar signal between two images. The advantage of this method is the possibility of analysing large areas in one single spot and very small movements, potentially up to 0.1mm per year can be detected. (European Association of Remote Sensing Companies) However, the costs of using satellite radar interferometry is relatively high.

1.2 Problem Statement

Landslides are among the many natural disasters causing massive destructions and loss of lives across the globe. Almost every landslide has multiple causes. Therefore, the real-time monitoring is one of the prime necessities to prevent the tragedy due to landslide happens. Hence, monitoring on the slope movement of the land is one of the effective methods as landslides are a down-slope movement of soil and rock under the direct influence of gravity. Previous researchers have used several methods to detecting the ground movement. However, the existing methods of detecting the ground movement were limited to single plane of movement per device.

1.3 Objective

a) To develop a low-cost tilt sensing device based on moiré fringe pattern theory for landslides monitoring using Raspberry Pi.
b) To develop an algorithm for the measurement of the centroid of moiré fringe pattern.

1.4 Scope of research

This study is limited to complete circle of moiré fringe pattern that are generated when two moiré gratings superimposed. Different moiré fringe patterns are generated by tilting the goniometer. The algorithm for detecting centroid of moiré fringe pattern will be developed with python and OpenCV. Tilt sensing device will be fabricated to produce the real moiré fringe pattern. This algorithm will be tested on simulated moiré fringe pattern and real moiré fringe pattern to prove the workability of algorithm.

CHAPTER 2

LTERATURE REVIEW

2.0 Overview

There is a long history involved in the prevention and mitigation of landslides. However, the movement of landslides is a complex process that depends on many factors. Therefore, real-time monitoring of landslides is one of the prime necessities of the world. Different methods for detecting and monitoring slope movement and landslides have been studied by many researchers for this purpose. This chapter introduces and reviews the landslide monitoring methods and tilt sensing device based on moiré fringe pattern theory that were used by previous researchers in monitoring the factors lead to landslide.

2.1 Landslide Monitoring Methods

Shi, Zhang, and Meng (2008) proposed the use of the optical fiber sensing technology in landslide monitoring. In their approach, the optical fiber sensing technology measured the change of certain parameters of the transmission light in fiber, and the parameter for this study is the slope movement. The sensor used are the optical fiber Bragg grating sensor (FBG) and the Brillouin time domain reflection sensor (BOTDR). The sensitivity of FBG sensor is high that measure the strain extremely accurately, but the sensing array which is used to response the surrounding is set in advance, researchers must measure these discrete distributed sensing spot respectively. Therefore, the monitor flexibility of FBG is low. The BOTDR sensing part is the optical fiber. It may be used to realize the long distance, the uninterrupted and distributed monitor. But for its technical limit, the measurement distance resolution of BOTDR is only achieved 1 m. Hence, Shi et al. combined FBG and BOTDR to offset the insufficiency of them as they laid the optical fiber in the entire landside mass and used BOTDR technology to obtain the outline information of the entire landside mass. They also installed the FBG sensor on the essential distort spot (distortion crack) in the landside mass and utilized its high measurement sensitivity characteristic to obtain the strain of the certain essential spots in landslide. However, the main challenging part is the difficulty in embedding the optical fibers in appropriate place for the real effective information, thus increases the cost of this system.

Vinodini Ramesh, Kumar, and Rangan (2009) developed a wireless sensor network for landslide detection. A sensor column that containing tiltmeters and strain gauges was designed for this system. The sensor column was used to measure the deformation caused by the slope movement. Besides the tiltmeters and strain gauges, the sensor column also connected to other geological sensor (such as geophone and dielectric moisture sensor) and same wireless sensor node. The data was successfully received from the deployment site with minimal data packet loss and analysis of data was able be performed. However, the sensitivity of the tiltmeters and other types of inclinometers is limited to a single plane of movement. For the detection of movement in multiple planes, this required the multiple sensors to achieve it.

A study was carried out by García, Hördt, and Fabian (2010) on landslide monitoring with high resolution tilt measurements a the Dollendorfer Hardt landslide, Germany. For their research, a borehole and platform tiltmeter that contain two independent electrolytic bubble tilt sensors (one for each tilt axis), of 0.1 µrad (1µrad = 1µm/m) nominal resolution, were installed to measure the internal deformation inside a landslide body. The tilt signal is dominated by long-term variation on a time scale of weeks to months. The long-term variation may be further decomposed into a trend that shown to be predominantly linear, and a seasonal variation. The trend indicates that the landslide undergoes small but continuous deformation. Although this system able to detect the slope movement, but the tiltmeters used can only measure in single-axis respectively. Without each of them, the multiple-axis detection may unable to carry out.

Uchimura et al. (2015) proposed a simple monitoring method of precaution and early warning of rainfall-induced landslides using tilt sensors. A set of equipment has been developed for practical uses, which is equipped with a Micro Electro Mechanical Systems (MEMS) tilt sensor (nominal resolution = 0.0025^{o} = 0.04mm/m) and a volumetric water content sensor (nominal resolution = 0.1%). These sets of equipment have been deployed at several slope sites in Japan and China, and long-term monitoring was attempted. Slope failure tests were also conducted on a natural slope by applying artificial Heavy rainfall. The developed system detected distinct behaviors in the tilting angles at these sites in the pre-failure stages. Considering the behaviors of tilting monitored on the surfaces of these slopes, researchers proposed that a precaution be issued at a tilting rate of 0.01^{o} per hour and a warning be issued at a tilting rate of 0.1^{o} per hour, to be on the conservative side.

A study was carried out by Uhlemann et al. (2016) on the assessment of ground-based monitoring techniques applied to landslide investigations. The monitoring systems used in this paper included active waveguides (AEWG), inclinometers, shape acceleration array (SAA), tiltmeter, tracking of GPS markers, weather station, and piezometers. The results highlight the relative performance of the different techniques, and can provide guidance for researchers and practitioners for selecting and installing appropriate monitoring techniques to assess unstable slopes. It showed that only a well-balanced choice of monitoring devices covering all scales of spatial and temporal resolutions delivers information that can be used to understand triggering mechanisms and deformation behavior of a slope in great detail.

Klimeš et al. (2012) proposed the monitoring of slow-moving landslides and assessment of stabilization measures using an optical-mechanical crack gauge. By superimposed two identical gratings, a tiny displacement in one of the grating will give rise to a large displacement in the elements of the moiré pattern. With this method, the ground movement can be detected even the movement is very slow or tiny displacement. However, the main limitations of the device are that personnel are required on-site and that monitoring is relative time-consuming.

2.2 Tilt Sensing Device Based on Moiré Fringe Pattern Theory

Juinn, Ratnam, and Ahmad (2014) developed a moiré-pattern based tilt sensor for slope movement sensing. The tilt sensing device was built up by placing one moiré grating (opaque background) on a custom-made liquid container, while superimposed another similar but fixed moiré grating with transparent background at the top of the liquid container. As the device was tilted, the images of the moiré pattern were captured and processed using programs to obtain relevant information about the tilt angle.

Tan, Ratnam, and Ahmad (2017) proposed a method for the feature extraction form moiré pattern images for tilt sensing. The image of moiré fringes captured were subject to several processing such as low-pass filtering, polar transformation etc. using MATLAB to study the relationship between tilt angle (θ) and peak-to-valley height (h_{pv}). The feature, namely the peak-to-valley height, was found to be effective in sensing tilt angles. This device has a potential to be used in landslide monitoring application due to the simple compact design and the ability to detect tilt in one plane.

2.3 Summary

It can be observed that some existing methods applied to detecting the ground movement are limited to single plane of movement per device. In order to detecting ground movement in several axes, two or more devices are needed. Besides that, detecting the ground movement from several aspects with different techniques able to provide information in great details, but this will increase the cost of the system. Therefore, low-cost tilt sensing device based on moiré fringe pattern theory will be develop in this research. Furthermore, some methods also facing the limitation such as personnel are required on-site and monitoring is relative time-consuming. Therefore, development of the low-cost tilt sensing device based on moiré fringe pattern theory will be carried out with the Raspberry Pi that works as portable mini processor.

CHAPTER 3

METHODOLOGY

3.0 Overview

In order to achieve the objectives, the Raspberry Pi equipped with OpenCV and Python was prepared before proceeding to the technique to solve the problem. First of all, the simulation of moiré fringe patterns via MATLAB software was done. Next, the development of the algorithm by using OpenCV and Python was required to determine the centroid of the moiré fringe patterns. Simulated moiré fringe patterns were tested with centroid detection algorithm to prove the workability of algorithm. Tilt sensor device with goniometer was set up to get the real moiré fringe pattern. The centroid detection algorithm was applied on real moiré fringe pattern and study the thresholding value for LED lights output. Thus, the thresholding value for LED lights output can be adjusted based on requirement. Finally, the application of completed algorithm on the real moiré fringe pattern and the results was recorded.

3.1 Simulation of Moiré Fringe Pattern via MATLAB

The simulation of moiré fringe pattern was computed based on the Moiré simulation algorithm of P.Y. Tan et al. (Tan et al., 2017) by using MATLAB software. The Moiré simulation algorithm was shown in Figure 3.1.

Firstly, a fixed circular grating G_1 was generated automatically, followed with second circular grating G_2 that generated according to the input value: x shift value (Δx) and y shift value (Δy). The image is then saved and subjected to moiré image processing algorithm as shown in Figure 3.2. Circular average filter was applied to saved moiré image to eliminate the grating lines. The intensity of the cropped image was increase by using function ‘imadjust’. Figure 3.3 showed the moiré fringe pattern simulated along the image processing.

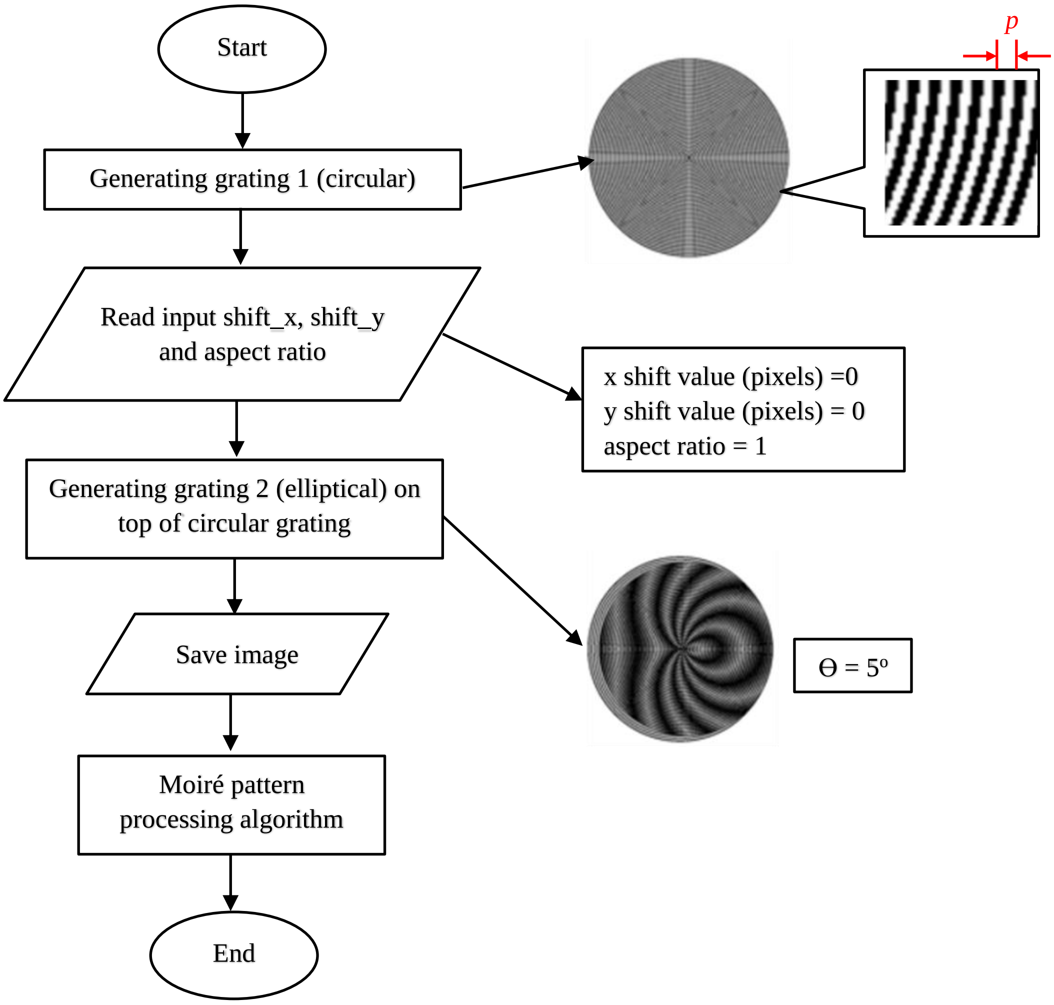


Figure 3.1: Moiré simulation algorithm (Tan et al., 2017)

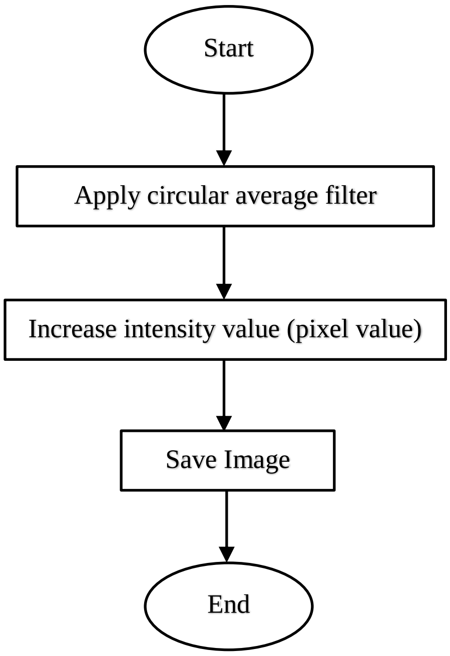


Figure 3.2: Algorithm for simulated moiré image processing

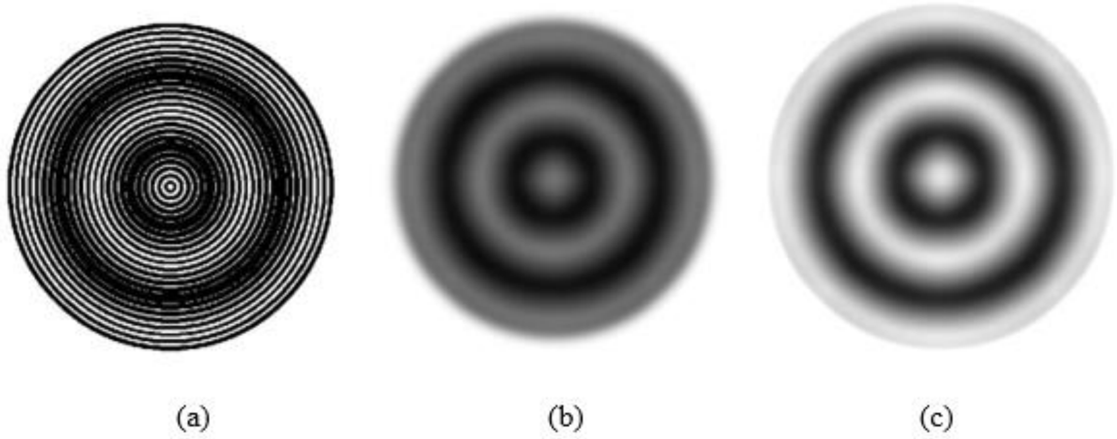


Figure 3.3: Moiré fringe pattern simulated with Δx = 0, Δy = 0: (a) Before image processing, (b) After circular average filter applied, (c) After intensity value increased

A list of number of moiré fringe patterns with different Δx value and Δy value was shown in Table 3.1. An example of simulated moiré fringe pattern for Δx = 0, Δy = 0 with the coordinate system of the shift direction is shown in Figure 3.4. These simulated moiré fringe patterns will be used to determine the workability of centroid detection algorithm.

Table 3.1: List of number of moiré fringe patterns with different Δx value and Δy value

Pattern number	x-coordinate to be shift	y-coordinate to be shift
1	0	0
2	0	1
3	0	2
4	0	3
5	0	4
6	0	5
7	0	-1
8	0	-2
9	0	-3
10	0	-4
11	0	-5
12	1	0
13	2	0
14	3	0
15	4	0
16	5	0
17	-1	0
18	-2	0
19	-3	0
20	-4	0
21	-5	0

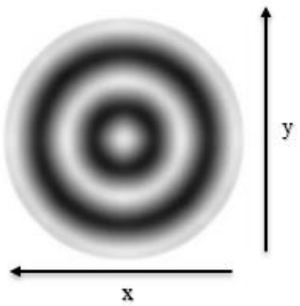


Figure 3.4: Simulated moiré fringe pattern for Δx = 0, Δy = 0 with coordinate system of shift direction

3.2 Centroid Detection Algorithm for Simulated Moiré Fringe Pattern

An algorithm with the purpose of detect the centroid of the moiré fringe pattern was developed by using OpenCV and Python software. Figure 3.5 showed the centroid detection algorithm for simulated moiré fringe pattern.

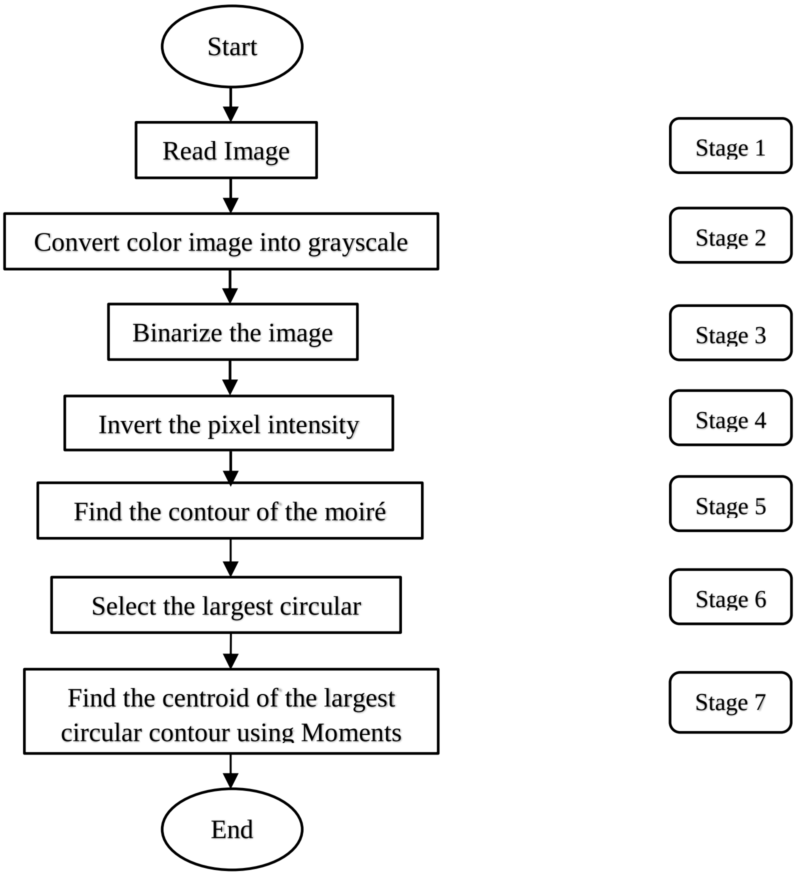


Figure 3.5: Algorithm for centroid detection for simulated moiré fringe pattern

Firstly, the image of the moiré fringe pattern was converted into grayscale by using cv2.cvtColor command. Binarization was applied to the grayscale image with thresholding pixel value of 100, which means the pixel values that below or equal to 100 will be converted into black colour (pixel value = 0), while the pixel values that above 100 will be converted as white colour (pixel value = 1). The pixel value of the binarized image was inverted by using np.invert command for the ease of following processes. By using cv2.findContours command, the contours of moiré fringe pattern were found and sorted in order, and contour for the moiré fringe pattern with largest completed circle after image processing was selected. The centroid of the selected contour was calculated via cv2.moments command. Moment is a certain particular weighted average of the image pixels' intensities. Moments provide a method of describing properties of object in terms of area, position, orientation, etc. Moment of an object can be defined via equation below:

$$m_{ij} = \sum_x \sum_y x^i y^j a_{xy} \tag{3.1}$$

where i + j = order of the moment

x, y = pixel coordinates

a_{xy} = pixel brightness

Zero moment can be defined as

$$m_{00} = \sum_x \sum_y a_{xy} \tag{3.2}$$

While the first moments can be defined as

$$m_{10} = \sum_x \sum_y x a_{xy} \tag{3.3}$$

$$m_{01} = \sum_x \sum_y y a_{xy} \tag{3.4}$$

For a binary image, the zero-order moment is same as the object area since a_{xy} is either 0 or 1.

And the centroid of the object can be obtained via the equations below:

$$Cx = \frac{M_{10}}{M_{00}}, Cy = \frac{M_{01}}{M_{00}} \tag{3.5}$$

Once the centroid was detected, the profile of largest contour after image processing will be drawn on the original image with yellow colour and the centroid will be marked. Figure 3.6 showed the processing stages of the images to detect the centroid based on the programming code.

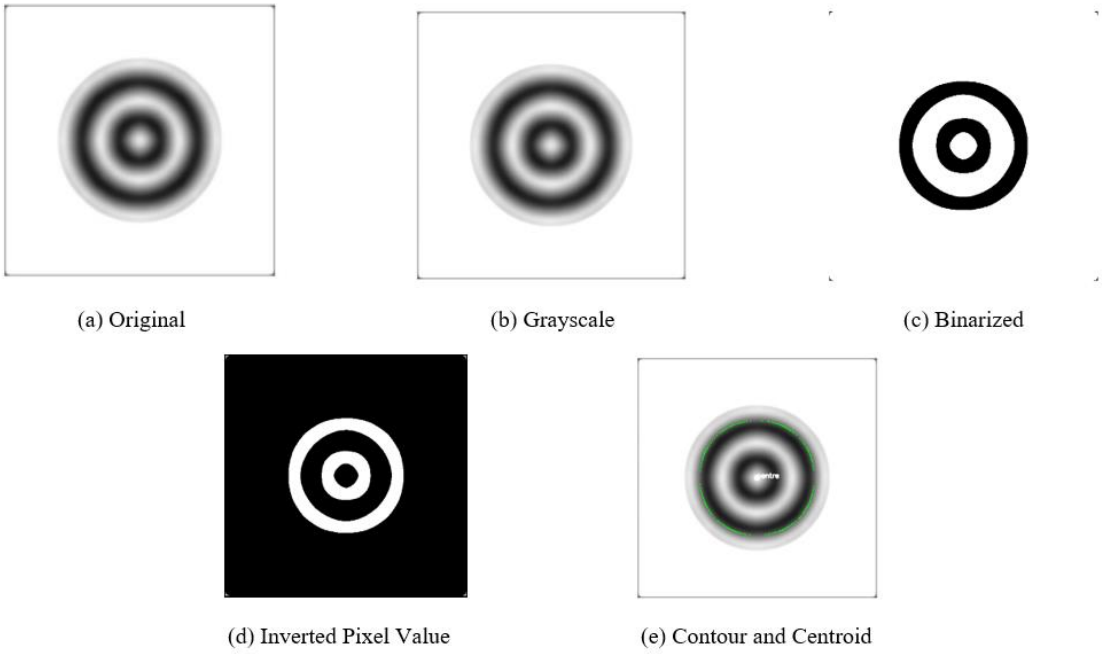


Figure 3.6: The processing stages of the images (a) original image; (b) grayscale image; (c) binarized image; (d) image with inverted pixel value; (e) image with drawn contour and centroid

3.3 Experiment set up for Tilt Sensing Device

After proving the workability of the algorithm, a prototype of tilt sensing device was built according to the design of P. Y. Tan. et al. (Tan et al., 2017). Figure 3.7 showed the schematic drawing of tilt sensing device. The upper grating is fixed while the lower grating can be tilted about the centre of rotation. *A* is the distance between centre of lower grating and centre of rotation, and *d* is the working distance between webcam and upper grating.

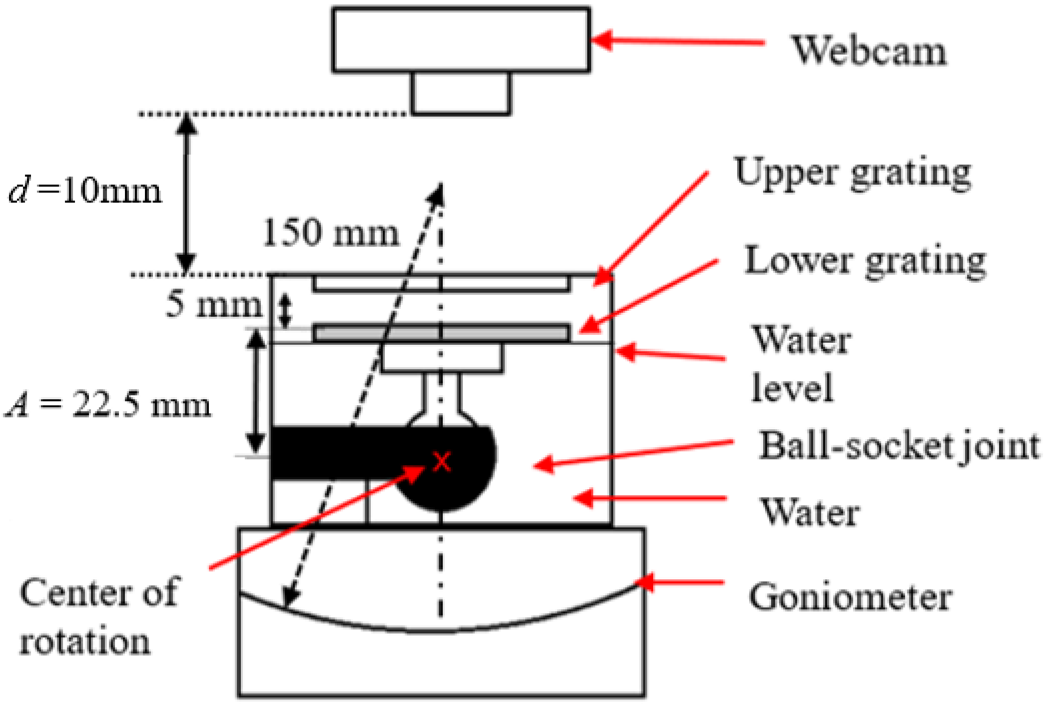


Figure 3.7: Schematic drawing of tilt sensing device (Tan et al., 2017)

The transparent square container was milled from 3mm thickness acrylic sheet and joined together by using chloroform. The lower grating was attached to a floater made by 5mm acrylic sheet. A ball-socket joint was used to join floater to the bottom of the container. Once the container was fabricated, water was filled into the container until the water level reached the bottom of lower grating as shown in Figure 3.7. Two $70mm^2$ metric goniometers with radius of curvature 150mm were stacked onto each other in perpendicular direction for the purpose of tilting the device in two different axes. The webcam used in this experiment set up is Logitech HD Webcam C310. The Logitech HD Webcam C310 was positioned above the upper grating. The webcam and the container were fixed on top of the goniometers to ensure the webcam and upper grating will tilt in same direction when the goniometers rotate, while the lower grating will remain on the horizontal level as it floating on the water surface. Figure 3.8 showed the top view of the tilt sensing device and the axes for rotation of goniometers.

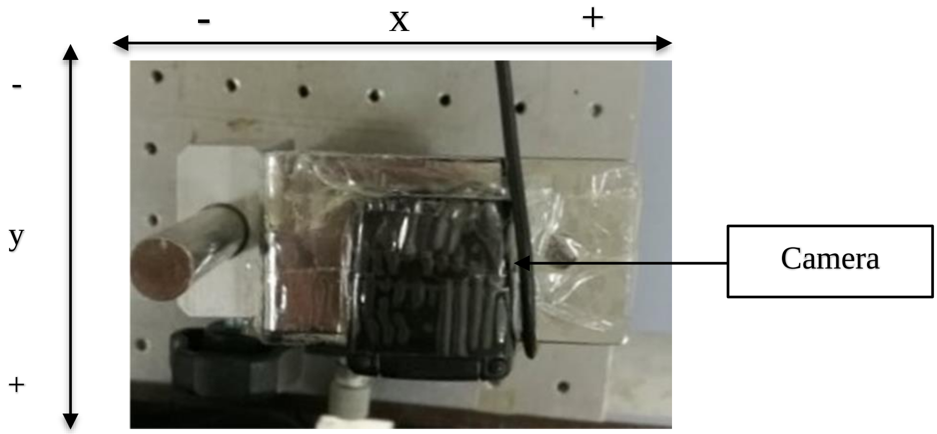


Figure 3.8: Top view of the tilt sensing device with the axes for rotation of goniometers

3.3.1 Camera working distance

Before connect the Raspberry Pi with the light-emitting diode (LED), the effect of camera working distance *d* between webcam and upper grating was investigate by carrying out an experiment using the setup as shown in Figure 3.9 due to the Logitech HD Webcam C310 does not equipped with auto focus function. The camera working distance was manipulated by changing the height of webcam to investigate the quality of moiré fringe pattern produced. With better quality of moiré fringe pattern produced, the complexity of image processing process in centroid detection algorithm can be reduced.

The images were captured by fixed the height of webcam at certain level when there is no any rotation made. The experiment was repeated with *d* = 10mm, 20mm, 30mm, 40mm and 50mm. Besides that, the goniometers will be rotated in x-axis and y-axis independently for each working distance. After that, the suitable camera working distance was determined.

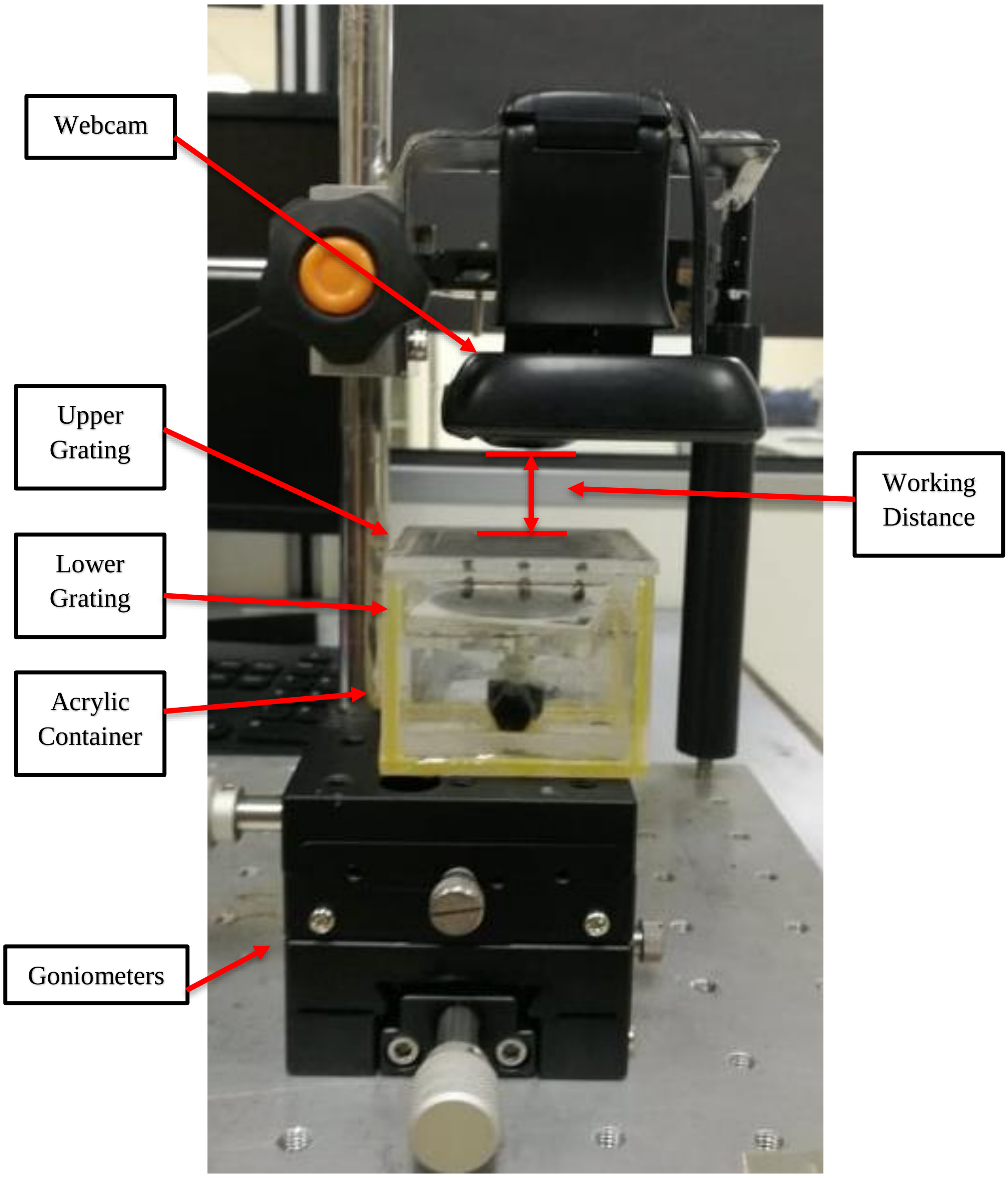


Figure 3.9: Experiment set up of tilt sensor device

3.3.2 Connection between Raspberry Pi and LED

Two white light LED strips were used as the illuminator of this project to provide uniform lighting and eliminate unnecessary shadow, as shown in Figure 3.10. The webcam was connected to Raspberry Pi to deliver the image captured for image processing. Two type of LEDs: green-light LED and red-light LED, were connected to the GPIO pin of Raspberry Pi via breadboard, jumper wires and two current limiting resistors with 1kΩ, for the purpose of receiving output signal. Green-light LED was connected to GPIO pin 8 while red-light LED was connected to GPIO pin 7. The wire connection of the Raspberry Pi and LED lights were shown in Figure 3.11. One goniometer was turned by 1° step until the range of ± 5° of one axis angles were obtained.

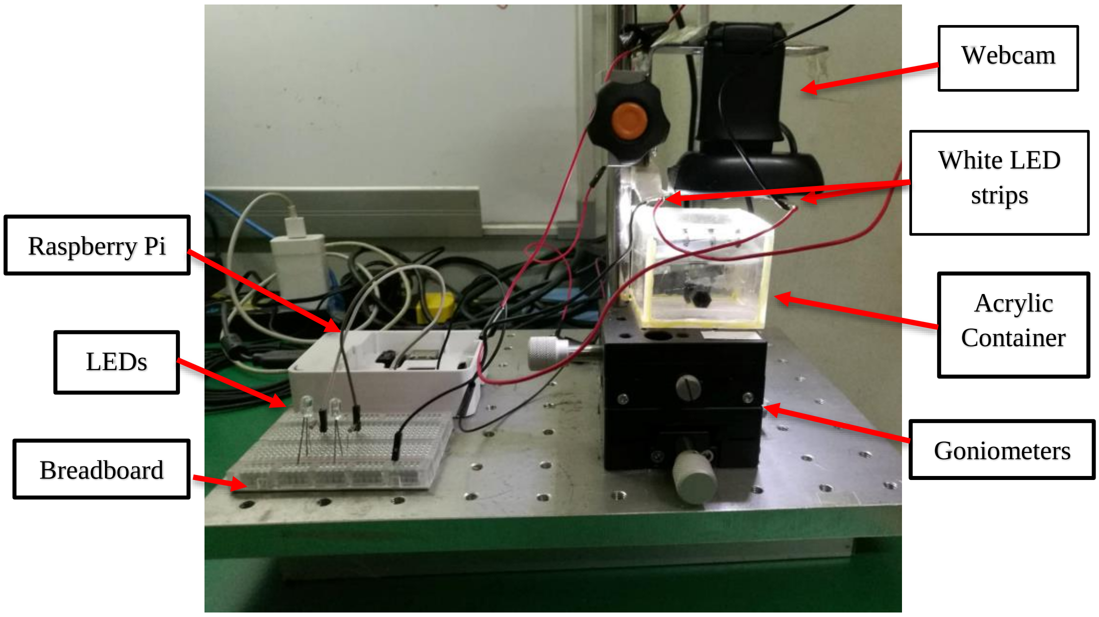


Figure 3.10: Experiment set up of tilt sensing device and Raspberry Pi

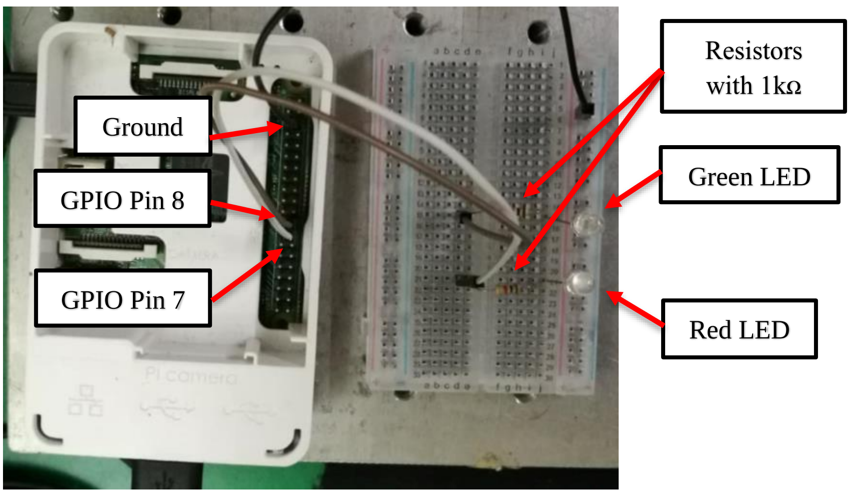


Figure 3.11: Wire connection of the Raspberry Pi and LED lights

3.4 Centroid detection algorithm for tilt sensing device

After setting-up the tilt sensing device, the centroid detection algorithm was modified according to the moiré fringe pattern produced. Figure 3.12 showed the centroid detection algorithm for moiré fringe pattern by real gratings.

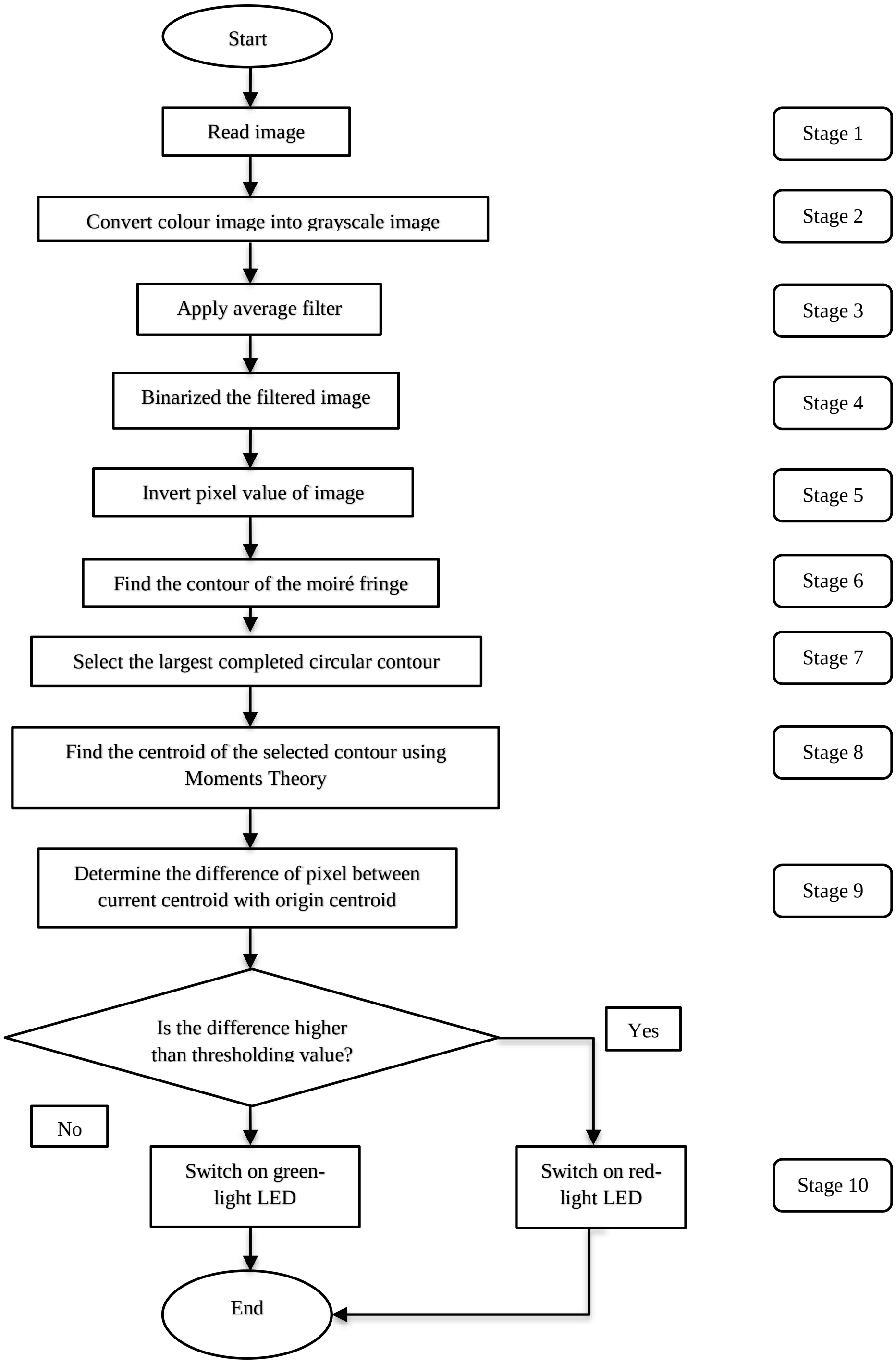


Figure 3.12: Algorithm for centroid detection for moiré fringe pattern produced by real gratings

The image is converted into grayscale using cv2.cvtColor command. Averaging filter with size 15 × 15 was applied to the image before transforming it into binarized image. The pixel value of the binarized image was inverted by using np.invert. Similar to previous algorithm, the contours of moiré fringe pattern were found using cv2.findContours command and sorted in order, and contour for the moiré fringe pattern with largest completed circle after image processing was selected. The centroid of the selected contour was calculated via cv2.moments command. The centroid of the contour was compared with the origin centroid (centroid for 0^o step rotation in both axes). If the difference between current centroid and origin centroid exceeding the predefined thresholding value, the output signal will switch on the red-light LED, indicates the device experienced excessive tilt. For the case which difference below thresholding value, green-light LED will lighted up. Figure 3.13 showed the processing stages of the images to detect the centroid.

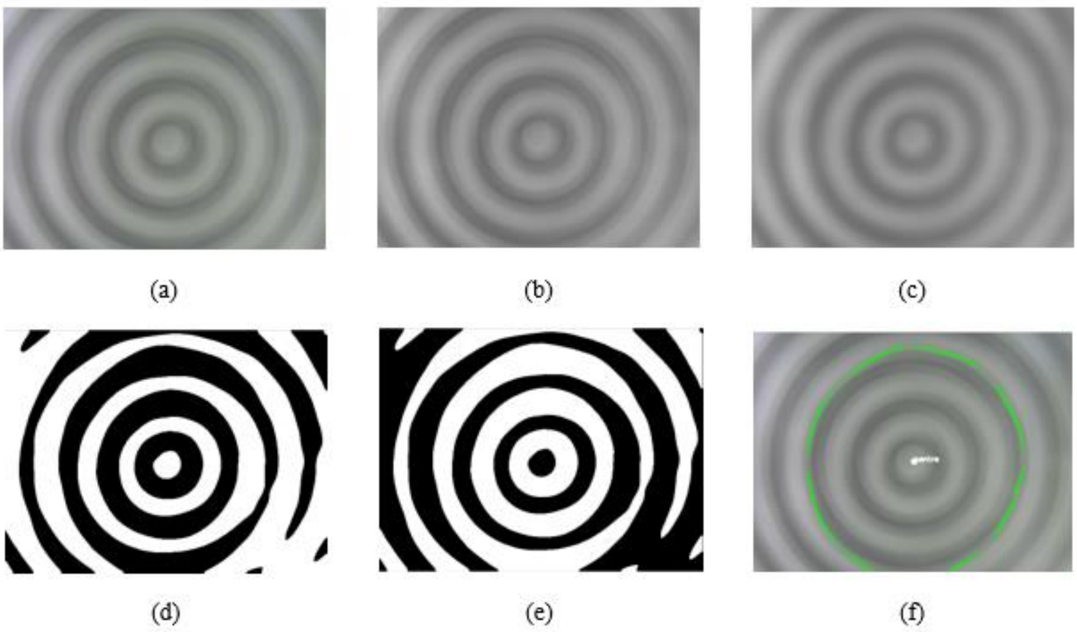


Figure 3.13: The processing stages of the image: (a) original image; (b) grayscale image; (c) filtered image; (d) binarized image; (e) image with inverted pixel value; (f) image with drawn contour and centroid

3.5 Summary

Simulation to generate the moiré fringe pattern was done by using MATLAB to obtain clear image of the moiré fringe pattern. Total of 21 moiré fringe patterns were simulated and tested with the centroid detection algorithm to study the workability of the algorithm. After the tilt sensing device was set up, the effect of camera working distance onto quality of moiré fringe pattern produced was studied by manipulated the height of the Logitech HD Webcam C310. Once the suitable camera working distance was determined, both red and green LEDs were connected to the Raspberry Pi as the signal of the output. The algorithm was applied onto the images of moiré fringe pattern that captured under different tilt angles and axis for further analysis.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Simulated moiré fringe pattern after applying centroid detection algorithm

The results after the centroid detection algorithm applied onto simulated moiré fringe pattern were shown in Table 4.1. The yellow colour line represented the largest circular contour after image processing that can be found in all simulated moiré fringe patterns. The centroid was plotted in the simulated moiré fringe pattern and its coordinate values were listed.

Based on the result, noticeable that the coordinate value of x-axis remained unchanged from pattern numbers of 2 until 11, and the coordinate value of y-axis remained unchanged for pattern numbers of 12 until 21. This is because for the pattern numbers of 2 until 11, the Δx value was zero during simulation moiré fringe patterns, while Δy value varies from -5 to 5, and vice versa. The relationship between shifted values for different axis during simulation of moiré fringe patterns and the centroid of the simulated moiré fringe pattern was shown in Figure 4.1 and Figure 4.2.

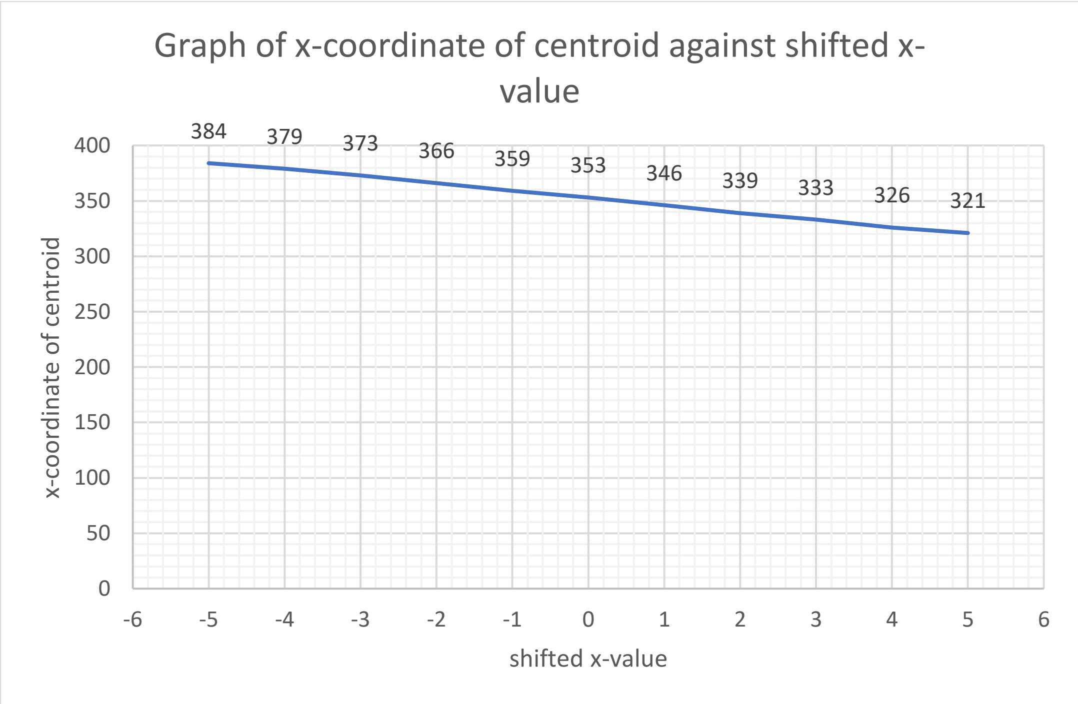


Figure 4.1: Graph of x-coordinate of centroid against shifted x-value

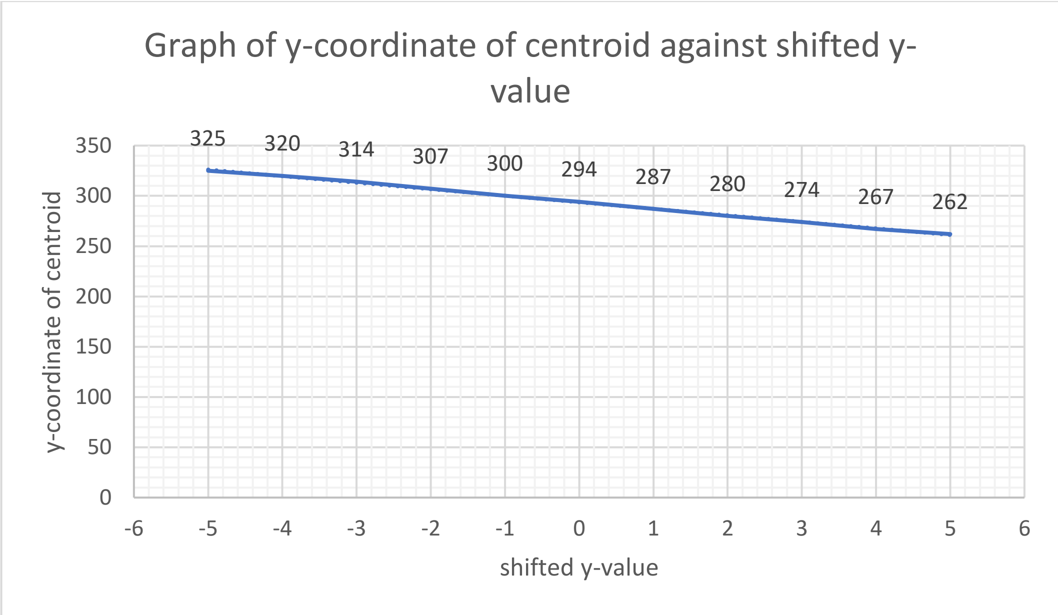


Figure 4.2: Graph of y-coordinate of centroid against shifted y-value

Based on Figure 4.1, the coordinate value of x-axis was decreased when the shifted x-value increased. This was because the coordinate system of Raspberry Pi was not same as the coordinate system of MATLAB. Figure 4.3 showed the coordinate system of MATLAB for simulation of moiré fringe pattern and the coordinate system of Raspberry Pi for centroid detection algorithm. Therefore, the coordinate value of x-axis was inversely proportional to shifted x-value. This trend also can be observed in Figure 4.2, the coordinate value of y-axis decreased as the shifted y-value increased. Since the algorithm able to plotted the yellow line to represent the largest circular contour of the simulated moiré fringe patterns after image processing to find its centroid, and the coordinate values of centroid were following trends without any noise value, this prove the workability of algorithm to detect the centroid of the moiré fringe patterns.

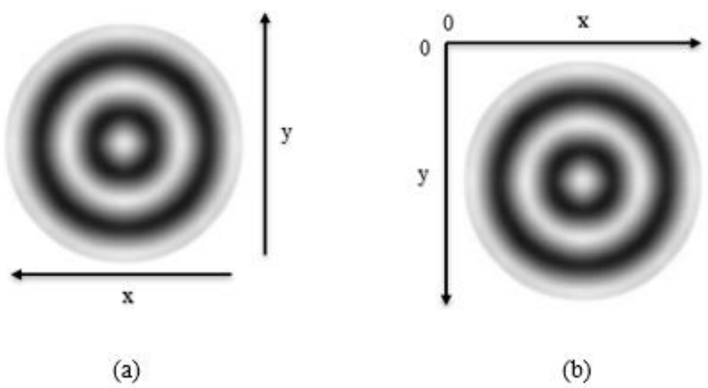
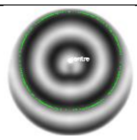
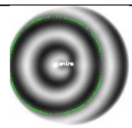
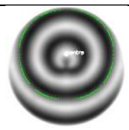
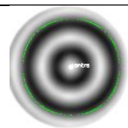
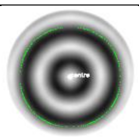
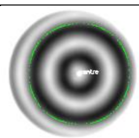
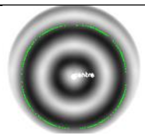
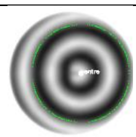
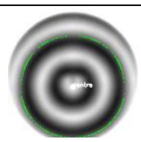
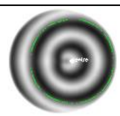


Figure 4.3: Coordinate system for: (a) MATLAB, (b) Raspberry Pi.

Table 4.1: Results for simulated moiré fringe pattern after algorithm applied

Pattern number	Results	Centroid	Pattern number	Results	Centroid
1		(353, 294)	12		(346, 294)
2		(353, 287)	13		(339, 294)
3		(353, 280)	14		(333, 294)
4		(353, 274)	15		(326, 294)
5		(353, 267)	16		(321, 294)
6		(353, 262)	17		(359, 294)
7		(353, 300)	18		(366, 294)
8		(353, 307)	19		(373, 294)
9		(353, 314)	20		(379, 294)
10		(353, 320)	21		(384, 294)
11		(353, 325)			

4.2 Camera working distance

The analysis for effect of camera working distance on image contrast/quality was done before the modification of centroid detection algorithm for moiré fringe pattern produced and the wiring connection between Raspberry Pi and LED. The working distance was tested with 10mm, 20mm, 30mm, 40mm, and 50mm. The moiré fringe pattern captured of each working distance with different tilted angles were shown from Table 4.2 until Table 4.6.

Table 4.2: Images captured under working distance of 10mm

Pattern Number	Tilted Axis, Angle	Image	Pattern Number	Tilted Axis, Angle	Image
1	No tilt		8	Tilt in y-axis with 1^{o}	
2	Tilt in x-axis with 1^{o}		9	Tilt in y-axis with 2^{o}	
3	Tilt in x-axis with 2^{o}		10	Tilt in y-axis with 3^{o}	
4	Tilt in x-axis with 3^{o}		11	Tilt in y-axis with -1^{o}	
5	Tilt in x-axis with -1^{o}		12	Tilt in y-axis with -2^{o}	
6	Tilt in x-axis with -2^{o}		13	Tilt in y-axis with -3^{o}	
7	Tilt in x-axis with -3^{o}