PATH PLANNING FOR MAXIMIZING THE POINT OF VIEW OF OBJECT USING ROBOTIC ARM WITH VISION

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DECLARATION

I declare that this thesis entitled "PATH PLANNING FOR MAXIMIZING THE POINT OF VIEW OF OBJECT USING ROBOTIC ARM WITH VISION" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : LEE SHU FANG

Date : ....

APPROVAL

I hereby declare that I have checked this report entitled "PATH PLANNING FOR MAXIMIZING THE POINT OF VIEW OF OBJECT USING ROBOTIC ARM WITH VISION" and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Mechatronics Engineering with Honours

Signature : ....

Supervisor Name : ....

Date : ....

DEDICATIONS

To my beloved mother and father

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ABSTRACT

Inspection is a major task for checking the defect of the objects in the manufacturing company. By inspection, it means that every part of the object should be inspected. Path planning for maximizing the point of view of object is the problem of creating motion profile for obtaining more information of the object with more points of view of the object given. The objectives of this project are to design and develop a path of points on the surface of an object to maximize the point of view of the object and to validate the path planning method using error analysis. In the proposed method, a path of 5 points is generated on the surface of the hemisphere, and the movement of the robot has used inverse kinematic and trigonometry function to ensure the webcam is pointed toward the center point of the object from one point to another point. There are three experiments to be conducted for this project, which are (1) study on the percentage of error based on the proposed method in generation of points and path on the surface of the hemisphere for the tip of the end effector of KUKA youBot to be positioned, (2) study on the validity of the proposed method in directing the tip of the end effector of KUKA youBot to face toward the center point of the hemisphere, and (3) study on the validity of the proposed method in directing the webcam mounted on the tip of the end effector of KUKA youBot to face toward the center point of the object. Based on the results obtained, a path of 5 points are generated on the surface of the hemisphere for maximal point of view. The tip of the end effector of KUKA youBot is able to be positioned on the points generated with an average percentage of position error of 1.67%. Then, the tip of the end effector is able to face towards the center point of the hemisphere with the average percentage of error of 2.91% for the angle from the center of hemisphere to joint 3 of the KUKA youBot and the average percentage of position error of 1.4%. The webcam that mounted on the tip of the end effector of youBot is also able to face toward the center point of the object with the average percentage of error of 3.05% for the position of reference line for the webcam to look at. Thus, it can be said that the proposed path planning method is valid. Lastly, it is concluded that all of the objectives of this project are successfully achieved after all of the experiments are completed.

ABSTRAK

Pemeriksaan adalah tugas utama untuk memeriksa kecacatan objek dalam syarikat pengilangan. Pemeriksaan bermakna setiap bahagian objek harus diperiksa. Perancangan laluan untuk memaksimumkan sudut pandangan objek adalah masalah dalam mencipta profil gerakan untuk mendapatkan lebih banyak maklumat mengenai objek tertentu dengan lebih banyak pandangan yang diberikan. Objektif projek ini adalah untuk merekabentuk dan membangunkan titik laluan pada permukaan objek untuk memaksimumkan sudut pandangan objek dan untuk mengesahkan kaedah perancangan laluan menggunakan analisis ralat. Dalam kaedah yang dicadangkan, titik laluan dijana pada permukaan hemisfera, dan pergerakan robot telah menggunakan kinematic songsang dan fungsi trigonometri untuk memastikan webcam ditujukan ke arah titik tengah objek dari satu titik ke titik lain. Terdapat tiga eksperimen yang akan dijalankan untuk projek ini, iaitu (1) mengkaji peratusan kesilapan berdasarkan kaedah yang dicadangkan dalam penjanaan titik dan laluan di permukaan hemisfera untuk hujung pengesan KUKA youBot ke diposisikan, (2) mengkaji kesahihan kaedah yang dicadangkan dalam mengarahkan hujung pengesan KUKA youBot menghadap ke arah titik pusat hemisfera, dan (3) mengkaji kesahihan kaedah yang dicadangkan untuk mengarahkan webcam dipasang pada hujung pengesan KUKA youBot menghadap ke arah titik pusat objek. Berdasarkan hasil yang diperoleh, laluan dengan 5 titik telah dihasilkan di permukaan hemisfera untuk titik maksimal pandangan. Hujung pengesan KUKA youBot dapat diposisikan pada titik-titik yang dijana dengan purata peratusan ralat kedudukan 1.67%. Kemudian, hujung pengesan KUKA youBot dapat menghadap ke arah titik pusat hemisfera dengan purata peratusan ralat sebanyak 2.91% untuk sudut dari pusat hemisfera ke gabungan 3 dari KUKA youBot dan purata peratusan ralat kedudukan sebanyak 1.4%. Webcam yang dipasang pada hujung pengesan youBot juga dapat menghadapi ke arah titik pusat objek dengan 3.05% purata peratusan ralat untuk kedudukan garis rujukan bagi webcam melihat. Oleh itu, boleh dikatakan bahawa kaedah perancangan laluan yang dicadangkan adalah sah. Akhirnya, disimpulkan bahawa semua objektif projek ini berjaya dicapai setelah semua eksperimen selesai.

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LIST OF ABBREVIATIONS

D.O.F	-	Degree of freedom
FYP	-	Final year project
ROS	-	Robot operating system
3D	-	3 Dimensional
CAD	-	Computer-aided drawing

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CHAPTER 1

INTRODUCTION

1.1 Motivation

In this era of technology development, the use of robots are becoming an unstoppable advancement due to their enhancement in performance, cost reduction, and according to the Boston Consulting Group, it has the ability to replace 25% of the labour tasks by the year of 2025 [1]. At the factory in Dongguan, which runs with the robotics have decreased the defect rate of their product from 25% to less than 5% [2]. This eventually has increased the quality and production of their product. Based on [1], the robots are expected to be used as the industrial tool over the decades due to their greatest potential. Therefore, with the addition of path planning for maximizing the point of view of the object using robotic arm with vision, the defect rate of the product could minimized because the defect of the product can be checked by maximizing the point of view, and thus increase the quality and production of the product.

Inspection is a major task for checking the defect of the objects in the manufacturing company. When a human is given a three-dimensional object and asked to memorize the visual of the object, the person will rotate or translate the object in order to study its appearance from different point of view [3]. Thus, human could recognize objects in images with little efforts, no matter the point of view or size of the object are different, nor when they are rotated or translated. However, for mass production, the quality assurance of all of the products is a very tedious job for human [4]. Normally, manufacturer tends to check one out of the 50 products [5], which will causes the quality of the other 49 products to be overlooked.

Table 1.1: Difference between robot and human inspector

Aspect	Robot	Human inspector
Work duration	Work tirelessly even for a long time	Get tired easily and need to rest after a certain time
Quality of product	Work consistently and repetitively. Thus, minimum error	Inconsistent and easily tired with repetitive work. Thus, error may increase over time
Speed of work	Work faster than human inspector	Work slower than robot

Based on the Table 1.1, robot can works longer than human inspector, this is because when there is mass production, robot can work tirelessly even for a long time, while human inspector will get tired easily and need to rest after a certain time of checking, which will causes more time to be taken. As for the quality of the product produced, due to the ability of the robot to work consistently and repetitively, minimum error will be occurred. On the other hand, error may increase over time if the human inspector works for a long time, because human work inconsistently and easily tired with repetitive work. Due to these reasons, speed of the robot to complete the task is faster than the human inspector, which eventually more quality product can be produced and the income of the manufacturing company can be increased. Therefore, a robot should be used for helping in inspection with maximum point of view of the object due to its advantages compared to the human inspector.

With the advancement of technologies, robotic arm with vision is widely used in manufacturing industry. Some manufacturer still uses several cameras at different location around the objects to be inspected, however, this system will only do the same repetitive task until it is programmed to do other task. Meanwhile, robots are more flexible due to their ability in reacting to different variables in their surroundings [4]. According to [6], multiple cameras are costly, while implementing a flexible robot is better. Therefore, this has motivated me to use a robotic arm with webcam mounted on the tip of the end effector of the robot manipulator to maximize the point of view of object, which the patches of the image of the object could be extracted for detecting defection problem. With these, in-line inspection can be done and gives advantages in cost saving and time saving.

For inspecting an object, maximizing the point of view of the object is important. Based on [7], there are several difficulties in inspecting the object, which the object could be in different position, different viewpoint, different scale or in rotated form. Therefore, more views obtained could get to know more of the parts of the object to check whether there is any defect. This means that by maximizing the viewpoints of the object, the quality of the product could be assured, because richer data of the object could minimizes the defects from identifying the imperfections of the product that human eye might miss [2].

Lastly, this robotic arm with vision will moves from a point to another through the developed path, while facing towards the inspection point of the object by taking more images of the object [6]. Thus, this could maximize the point of view of the object and reduce the time consumption in doing it, which eventually reduce the defection problem because even the smallest defect can be detected faster and more accurate than before.

1.2 Problem statement

When the surface of the object is large, a camera that fixed in a location could only detect a part of the object from a single point of view. Multiple points of views are required in taking more images of the object. This means that a flexible robot is required in moving the camera from one point to another. Therefore, this project will be using a 5 degree-of-freedom (D.O.F.) robot manipulator with webcam mounted on the tip of the end effector of it.

Workspace is the volume of space, it is important because the points that can reach by the tip of the end-effector of robotic arm must situated within it [8]. Path planning is a problem of reaching a desired point from another point in the workspace, while achieving a certain requirements including the shortest path [9]. In this project, path planning problem is focusing on fulfilling the requirement of maximizing the point of view of a certain object while ensuring shortest path. On top of this requirement, the problem of the plan includes ensuring the most efficient way to achieve by ensuring the tip of the end effector of the robot manipulator is facing towards the center point of the object.

It is important in specifying the path in much more detail rather than simply stating the final location to be reached by the robot manipulator. To solve this requirement, generating a sequence of points between the start and final position is necessary [8]. Generating viewpoints is a problem in maximizing the point of view of the particular object with the addition of coverage of the object's views for providing more detail of the object. In this project, maximizing the point of view of the object is a concern with the methods of generating viewpoints surrounding the object. This includes how to generate a path through the generated points. The more views or images obtained from the object, the more coverage of the object is obtained.

Robot limitation is also the problem in this project. Due to the continuous motion is made between the points in the path, there are several limitation of the robot manipulator that might be faced related to the singularities and workspace [8]. Therefore, limitations such as singularity, and initial and final point is unable to reach in the same solution [8] will be taken into consideration. Meanwhile, limitation such as unreachable point between the initial and final point will not include in the scope due to maximizing the point of view of the object is the main concern.

Furthermore, there is also a problem in this project in ensuring the tip of the end effector is facing toward the center point of the geometry shape, and the webcam that mounted on the tip of the end effector of the robot manipulator is facing in the direction toward the center of the object from a point to another through the path formed. Therefore, coordinate of the reference frame of the robot manipulator, coordinate of the tip of the end effector, coordinate of the last joint of the robot manipulator which can change the direction of the webcam, coordinate of the points formed through the path, coordinate of the center point of the object and center point of the geometry shape, and position of the webcam mounted on the tip of the end effector of the robot manipulator must took into consideration, in order to ensure the tip of the end effector of robot manipulator that moving towards the points is accurate by ensuring it is facing towards the center point of the geometry shape formed, while the webcam mounted on it is facing toward the center point of the object.

1.3 Objective

The objectives of this project are:-

1. To design and develop a path of points on the surface of an object to maximize the point of view of the object.
2. To validate the path planning method using error analysis.

1.4 Scope and limitation

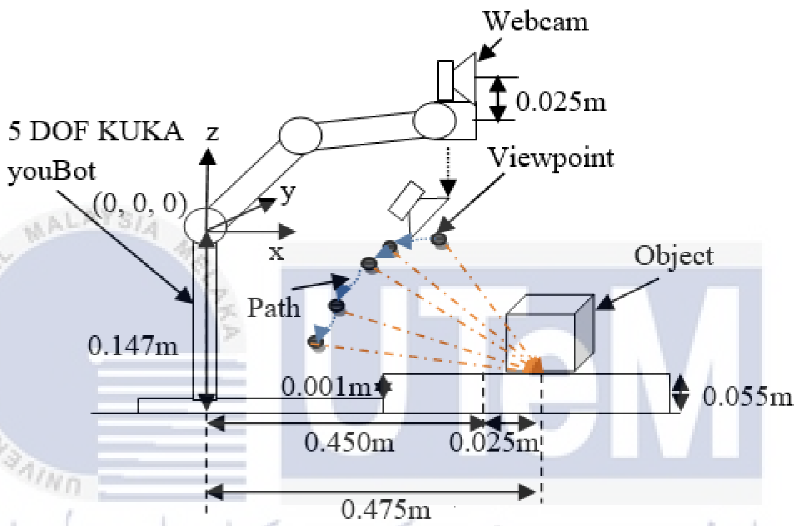

Figure 1.1: System description

The scope of this project is based on Figure 1.1 above, it is an overview of this project system for path planning for maximizing the point of view of object using robotic arm with vision. Firstly, the center point of the hemisphere is plotted on the surface of the platform at the coordinate of (0.45, 0, -0.137)m and the center point of the object is plotted at the coordinate of (0.475, 0, -0.137)m. All the measurements will be referred to the reference frame of KUKA youBot at (0, 0, 0) as shown in Figure 1.1. When the coordinate of the center point of the object, center point of the hemisphere and reference frame are known, MATLAB will be used to construct an imaginary hemisphere with the radius of 0.287m and center point of (0.45, 0, -0.137)m, for generating a sequence of points on the surface of the hemisphere in order to maximize the point of view of the object.

After that, a robotic arm with vision is replaced with a 5 D.O.F KUKA youBot with a webcam mounted on the tip of its end effector with difference of

0.025m. The ROS software will be used to move the robot manipulator, in order for the tip of the end effector of KUKA youBot able to point toward the center point of hemisphere and the webcam that mounted on the tip of its end effector is able to point towards the center point of the object. Singularity of this robot manipulator will also take into consideration in order to ensure the webcam and the tip of the end effector of the robot manipulator are moving to the accurate position, while facing towards their center point respectively. The position and orientation of the joints of KUKA youBot based on the developed path will be done off-line.

The limitations of this project are only static object will be tested, the object cannot be bigger than 0.077m x 0.081m x 0.056m, and it will be tested if and only if the object is situated on the surface of the center point for object. Also, due to the reason that this project only used the 5 D.O.F KUKA youBot without its mobile platform, the KUKA youBot could not face towards the center point of the object through horizontal line, thus the path of points will only be formed in vertical line. Then, obstacle in the workspace will be ignored, and 3D model extraction, image processing and classification are out of the scope for this project.

1.5 Outline of the report

This report has divided into 5 chapters, which are the introduction, literature review, methodology, results and discussions, and conclusion and recommendations. The first chapter is the introduction that has included the motivation, problem statement, objectives, and the scope and limitation of this project. For chapter 2, it is the literature review that has discussed about the previous research that related to this project. Analysis, synthesis and evaluation of the information from the previous research are done in chapter 2. For chapter 3, it is the methodology that has included project methodology, theoretical background of the method that will be used for this project, research overview, experiment setup, materials and equipment used, experiments with their specific objectives, equipment or materials used and procedures, method for analysis and reliability of the data. After that, the results and discussions for the three experiments will be analyzed in chapter 4. Lastly, chapter 5 is about conclusions and recommendations, which the conclusions and future work for this project are explained.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will discuss about the method used in the previous research that is related to this project. Studies that are related to path planning for maximizing the point of view of the object have focused on the vision on the end effector of the robot manipulator and the method used for inspection. Based on the previous method used for inspection, methods used for viewpoints generation, path planning for path generation, and position and orientation of the robot manipulator are also discussed in this chapter. Suitable methods to be used in this project are chosen for the tip of the end effector of the robot manipulator, points generation, path generation, and position and orientation of the robot manipulator.

2.2 Vision on the end effector of the robot manipulator

The end effector of the robot manipulator can reach a point given by a specific orientation of the end effector. This can be seen which the robot manipulator’s end effector can be applied on various application by equipping the end effector with tools such as grippers, sensors, robotic hand, spray, webcam, and others [10]. Based on the previous research on visual inspection, [11]–[15] have used a scanner on the robot manipulator’s end effector, [16], [17] has used a webcam on the end effector of the robot manipulator and an additional of turntable for the object to be situated on it by [17], and [18]–[20] have mounted a sensor on the robot manipulator’s end effector . Based on [14], when an end effector is mounted with a scanner, it becomes more easy to operate and less time-consuming. Based on [16], it said that fixing a vision system at a fixed location will obtain limited images of the object. Therefore, for this project, a webcam will be mounted on the tip of the end effector of the robot manipulator, so that it will be faster and easier in operating, and providing a wider area for capturing the images of the object by maximizing the point of view around the object.

2.3 Method used in previous research for inspection

Inspection is a major task for checking the defect of the objects in the manufacturing company. By inspection, it means that every part of the object should be inspected. During searching the research that related to path planning for maximizing the point of view of the object, most active research is in inspection. Therefore, the method used in the previous research of [11]–[20] for inspection problem is compared in the Table 2.1 below.

Table 2.1: Comparison between the methods used for inspection

Methods used for inspection	Target object		Model	
	Unknown	Known	Using CAD model	Not using CAD model
• Model framework extraction • Scan region segmentation • Viewpoint generation • Scan path generation	Yes, target object is unknown to the system [11], [12], [17], [18], [20]	No	Yes, CAD model is used [11], [12], [17], [18], [20]	No
• Reverse engineering	Yes, target object is unknown to the system [15]	No	Yes, CAD model is used [15]	No
• Rough scanning for collecting the information of the object for finding missing region • Specific scanning for scan path generation	Yes, target object is unknown to the system [14]	No	No	Yes, CAD model is not used [14]
• Model framework extraction • Viewpoint generation • Path generation	No	Yes, target object is known to the system [13]	Yes, CAD model is used [13]	No
• Design of configuration space, fixed step	No	Yes, target object is known to the system [16]	No	Yes, CAD model is not used [16]
• viewpoint generation • Path generation	No	Yes, target object is known to the system [19]	No	Yes, CAD model is not used [19]

The methods used in previous research for the case of inspection are compared in Table 2.1. There are two types of inspection, which the target object for inspection is either known or unknown to the system. After that, whether CAD model is used or not for the system is discussed too. Based on Table 2.1, when CAD model is used in the previous research, no matter the target object is known or unknown to the system, method such as using model framework extraction, viewpoint generation and goes by path generation is done [11]–[13], [15], [17], [18], [20]. Meanwhile, if CAD model is not used, no matter the target object is known or unknown, the method of viewpoint generation and path generation for inspection are also done [14], [19]. There are other methods used in previous research, such as when the target object is known and CAD model is not used, fixed step on the workspace is done, which the path for the sequence of viewpoint is done before the inspection [16]. Therefore, due to path planning for maximizing the point of view of the object is the main concern, viewpoint generation and path generation will be used. However, this method will be done off-line, so no matter the object is known or unknown to the system, CAD model will not be used and the path is fixed with the most optimized sequence of viewpoints.

2.4 Viewpoints generation

Due to the reason that viewpoint generation are mostly done in previous research on maximizing the point of view of an object, the methods used for viewpoints generation that have previously done in [11]–[15], [17]–[20] are compared in Table 2.2.

Table 2.2: Comparison between the methods used for viewpoints generation

Design	On the surface of the object	On the surface of a geometry shape surrounding the object
Method	• Generation of viewpoints on every tip of the triangular mesh model that situated on the surface of the object [11]; • Using search-based planning algorithm [12]; • Randomly sampling within the ellipsoid hemisphere surrounding the object [13]; • Using point cloud on the 3D information of the object [14], [15] and chord length discrete method for missing region [14]; • Using perception on the 3D geometry input of the object [19]; • Entity-based aspect graph on the input object [20]	• Generation of viewpoints by search space on the surface of the sphere using viewpoint planning algorithm [17], [18]
Geometry shape used for the method	• Triangular mesh model on the surface of CAD model [11], [13]; • Points within the ellipsoid hemisphere [13]; • Visibility invert cone concept on the surface of the circle of the workplace [14]; • 3D geometry input using geometry scripts with logic operations [19]	• Sphere [17] and tessellated sphere [18] surrounding the object with viewpoints pointing towards the center of the object

Based on Table 2.2, there are two ways in generating viewpoints, which the viewpoints are either generated on the surface of the object that extracted on a software as shown in Figure 2.1 or on a geometry shape surrounding the object as shown in Figure 2.2.

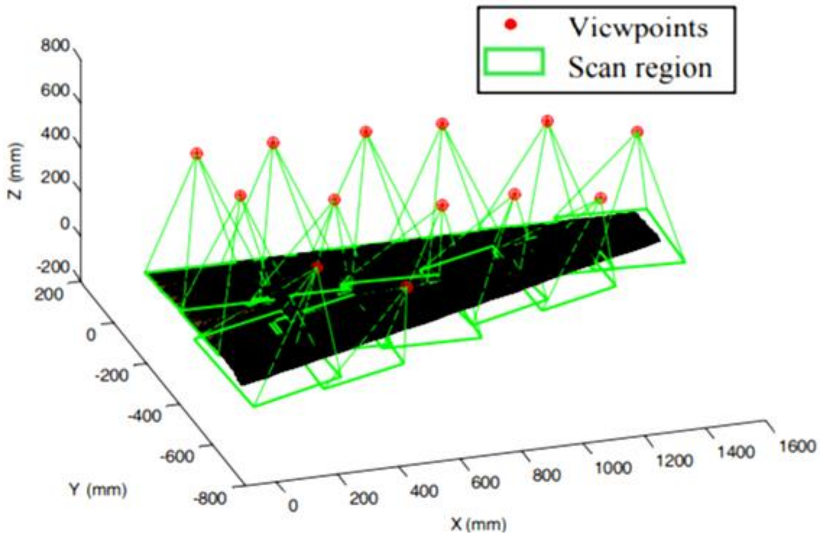

Figure 2.1: Viewpoints generated on the surface of the object that extracted on a CAD [11]

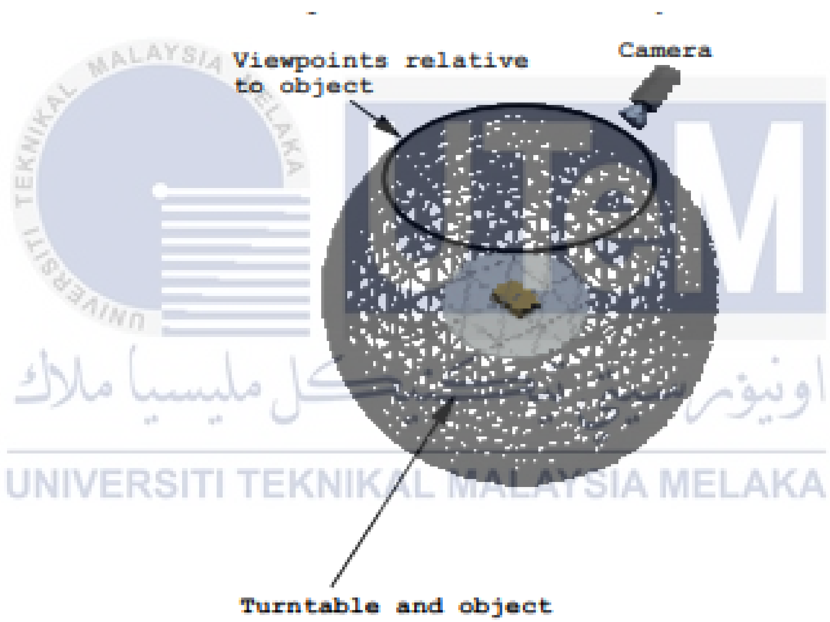

Figure 2.2: Viewpoints generated on the surface of a sphere surrounding the object [17]

For viewpoints that are generated on the surface of the 3D shape that extracted on a software have included the generation of points on the tips of the triangular mesh model that situated on the object surface [11] as shown in Figure 2.1, the used of algorithm [12], [13], [19], [20], the used of point cloud [14], [15] and the used of chord length discrete method [14]. From this method, several geometry shape has been applied, such as triangular mesh model as shown in Figure 2.1, invert cone which formed on the surface of the object, ellipsoid hemisphere which points formed within it and for [19], the extracted object is replaced with 3D geometry using geometry scripts and the points are generated on it. Based on Figure 2.1, after the object is extracted on a CAD, triangular mesh model is formed on the surface of the object, and the viewpoints are then generated on the tip of each of the triangular model.

On the other hand, generating viewpoints on the surface of a geometry shape that surrounds the object that situated at the center of the geometry shape has done in [17], [18]. Viewpoint planning algorithm has been used to generate viewpoints on the surface of the geometry shape of sphere that surrounding the object with viewpoints pointing toward the center of the object. Based on Figure 2.2, a sphere is formed first, after the object is extracted, viewpoints are generated on the surface of the sphere relative to the object through the search space using viewpoint planning algorithm.

Therefore, based on the previous research, hemisphere will be used as a geometry shape for this project due to other shape such as triangular mesh and cone are done on the surface of the model that extracted on the software, which this method is out of the scope for this particular project. In addition, generate viewpoints on the extracted model is taking longer time, while a geometry shape constructed for generate viewpoints is faster [10]. Thus, after the hemisphere is generated, points will then be distributed on the surface of hemisphere, and goes by points generating on the surface of the object.

2.5 Path planning for path generation

Due to the reason that maximizing the point of view of object is focused for this project, path planning for path generation is also one of the important process in this project in order to generate a path between the initial point and the final point, while ensuring all of the points generated are within the path. Therefore, the constraints for path planning, methods used for path generation for several path planning purposes, and their advantages that have previously done in [11]–[20] related to their design of location of points have shown and compared in Table 2.3.

Table 2.3: The constraints for path planning, methods used for path generation for several path planning purposes, and their advantages related to their design of location of points

Design	Points generated on the surface of the object	Points generated on the surface of the geometry shape surrounding the object
Constraint for path planning	• Field of view [11], [13], [14], [19], [20]; • View angle [11], [13], [19]; • Working distance [11], [16]; • Overlap [11], [19]; • No occlusion [13]; • Circle of vision [14]; • Number of points, delay time, process cycle time [16]; • Resolution, focus, visibility [19], [20]	• Face visibility [17]; • Measurability for baseline distance between the camera viewpoint and the light source viewpoint and viewability with the uncertainty of the pose [18]
Method used for path planning in path generation	• Shortest path and high accuracy path: Using search-based planning algorithm [12], using ants algorithm [19], and using genetic algorithm [20]; • High accuracy path: Using commercial software [15]; • Coverage planning and stability: Using Markov design process formulation with reinforcement learning based tree search algorithm [13]; • Shortest path, high accuracy path, coverage planning and stability: connecting each viewpoint in clockwise direction and using cubic spline interpolation method [14]; • Time-optimal: Path is planned [16]	• Shortest path: Using planning algorithm [17] and using simulated annealing algorithm [18]
Advantage	• Accurate [12], [14], [15], [19], [20]; • Fast [12], [14], [19], [20]; • Stable and high coverage ratio [13], [14]; • Time optimal [16]	• Less point of view but full coverage of the object is achieved [17]; • Accurate [18]

Based on Table 2.3, a sequence of points will be generated for path planning purposes, which the path will based on the points generated either on the surface of the object or on the surface of the geometry shape surrounding the object. However, there are some constraints for path planning to ensure the effectiveness of the path planned. Constraints such as field of view, view angle, working distance, overlap, no occlusion, circle of vision, number of points, delay time, process cycle time, resolution, focus, visibility, measurability and viewability have concerned in path planning from the previous research.

Path planning is a method used for the robot manipulator to find the shortest or optimal path in moving from a point to another point within the workspace [9]. As for the method used for path planning in generating a sequence of viewpoints, algorithms such as genetic algorithm, ants algorithm, simulated annealing algorithm and others have been used for obtaining the shortest path in previous research. The method of using algorithm for shortest path purposes have been used in both of the design, which the points are either generated on the surface of the object or generated on the surface of a geometry shape surrounding the object. This can be seen that shortest path algorithm is widely used in many applications for finding the shortest paths between the points in a workspace. In addition, connecting of each viewpoint in clockwise direction has also used for obtaining the shortest path. Then, with the use of algorithm in [17], full coverage of the object view with minimal point of view is ensured too.

Not only that, high accuracy path is also obtained by using the algorithms for shortest path. In addition, other commercial software and connecting of points in clockwise direction have also ensured that the error occurred is minimized, thus higher accuracy path can be obtained and the quality of the system can be improved. Meanwhile, path planning for obtaining the full coverage of the object is achieved by using Markov design process formulation with reinforcement learning based tree search algorithm.

Furthermore, in order to ensure the stability of the system, methods such as using reinforcement learning and using cubic spline interpolation are done. By ensuring the stability of the system, error by vibration and shock can be reduced. Moreover, time-optimal is achieved by knowing the configuration space, which the planning of the path in done off-line. Therefore, this project will be focused on obtaining the optimal path that minimizes the amount of turning, in order to ensure the generated path can be complete with minimal time consumption, while ensuring maximal point of view of the object.

2.6 Position and orientation of the vision mounted on the end effector of the robot manipulator to the sequence of viewpoints formed from path generation

Based on the previous research related to the position and orientation of the vision mounted on the end effector of the robot manipulator, coordinate transformation between the position of the object and the base of the robot manipulator, and between the position of the scanner and the end effector of the robot manipulator are done in [11], in order to ensure the robot moves in the accurate position. In addition, these coordinate transformation has also applied in [17], [18], which joint angles for the each of the joint is known. Meanwhile, there is also an alternative way, which when the position and orientation of the desired point is given, joint angles can be solved using inverse kinematics that consisted of two approaches, either analytical or numerical solution [8][21]. In [13], inverse kinematics is used with the IKfast algorithm. However, for this inverse kinematic solver, if the calculation of it is failed, the specific viewpoint will be excluded from the set of viewpoints. Due to the reason, some viewpoint might be eliminated when using the IKfast algorithm. As for [21], analytical approach of inverse kinematic is used, where redundancy parameters are proposed to use the computed IK solution to extract the base position. Therefore, for this project, due to the reason that the coordinate of the points will be known from the generated path of points, inverse kinematic will be used by giving the coordinate of the points to obtain the joint angle, which will then measure the position of the tip of the end effector of the robot manipulator. Thus, the webcam that mounted on the tip of its end effector could moves accurately on the sequence of points formed from the developed path, while ensuring the webcam is facing towards the center of the object.

2.7 Summary of the chapter

In short, based on the previous research, it is recommended to use a vision mounted on the end effector of the robot manipulator because it is easier and less time consuming in operating. Thus, a robot manipulator with a webcam mounted on its end effector will be used in this project. For viewpoints and path generation, it is widely used in previous research in inspection, which the points are either generated on the surface of the object or on the surface of the geometry shape surrounding the object, then continued by forming a path from the initial point to the final point by ensuring shortest, accurate and time optimal path are achieved. Based on the research on forming a sphere surrounding the object, it can ensure the viewpoints on the geometry shape is able to point towards the center of the object while ensuring full coverage of the object is achieve, while forming points on the surface of the object could ensure optimized path. Therefore, in this project, generating a path of points on the surface of the object will be used by using the geometry shape of hemisphere first. In the research on position and orientation of the vision mounted on the end effector of the robot manipulator, there are two kinematics in doing it, which is either coordinate transformation by forward kinematic or inverse kinematic. Due to the sequence of points obtained will be giving coordinate, thus inverse kinematic is needed to obtain the joint angles, in order to ensure the robot manipulator moves in the correct position, which the webcam is able to face towards the center point of the object and the tip of the end effector of the robot manipulator is able to face towards the center point of the hemisphere by touching one point to another point formed from the path.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discussed about the project methodology, theoretical background of the method that will be used for this project, research overview, experiment setup, for the whole project in order to achieve the objectives of this project, materials and equipment used, method for analysis and reliability of the data. This chapter has also discussed three experiments and each of the experiments had their respective objectives, materials and equipment used and the procedure for doing that experiment. The experiments for completing this project have included (1) study on the percentage of error based on the proposed method in generation of points and path on the surface of the hemisphere for the tip of the end effector of KUKA youBot to be positioned, (2) study on the validity of the proposed method in directing the tip of the end effector of KUKA youBot to face toward the center point of the hemisphere, and (3) study on the validity of the proposed method in directing the webcam mounted on the tip of the end effector of KUKA youBot to face toward the center point of the object.

3.2 Project methodology

The flowchart for the project methodology gives an insight on the process of this project that start from researching on the related work until analyzing of the experimental test is shown in Figure 3.1.

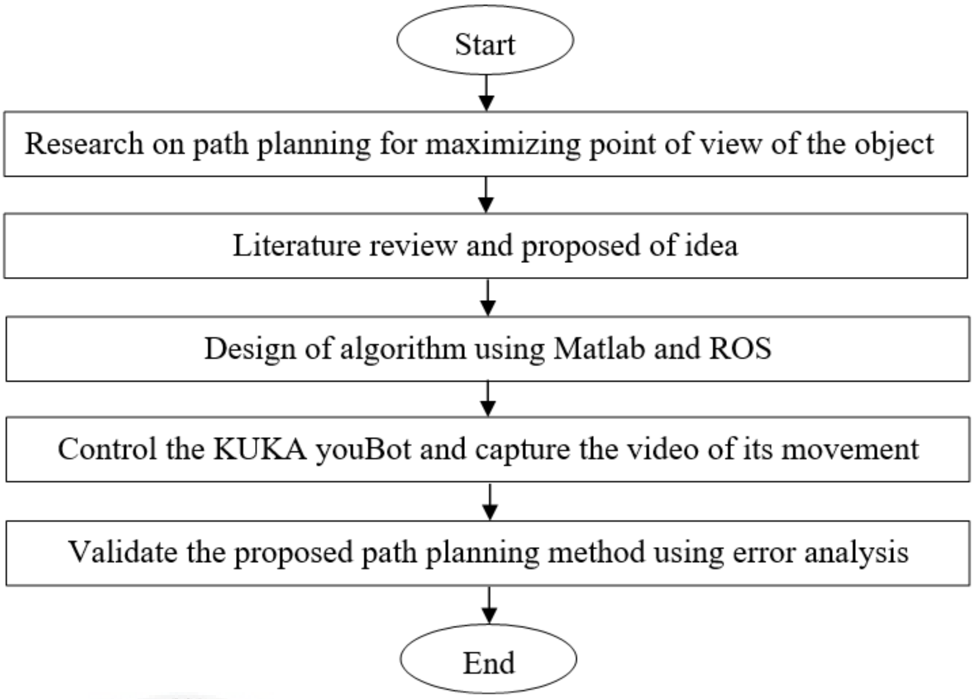

Figure 3.1: Project methodology

Based on the project methodology flowchart that shown in Figure 3.1, at the start of this project, research on the related works such as path planning for maximizing the point of view of the object are done. After that, the research works are analyzed, synthesized and evaluated, in order to propose the idea on conducting this project. After planning the method to conduct the experiment, design of algorithm using various software such as MATLAB and ROS are used to generate points and path on the surface of the object for the tip of the end effector of the KUKA youBot to be positioned, to direct the tip of the end effector to face towards the center point of the hemisphere that situated on the surface of the platform, and to direct the webcam mounted on the tip of the end effector of youBot for capturing the video of the object that situated on the center point of the object respectively. The KUKA youBot is then controlled using ROS and its movements are captured. Then, the performance of the KUKA youBot in terms on error is analyzed.

3.3 Theoretical background

The theoretical background of the method flowchart as shown in Figure 3.2 gives an insight on the method that will be used for this project.

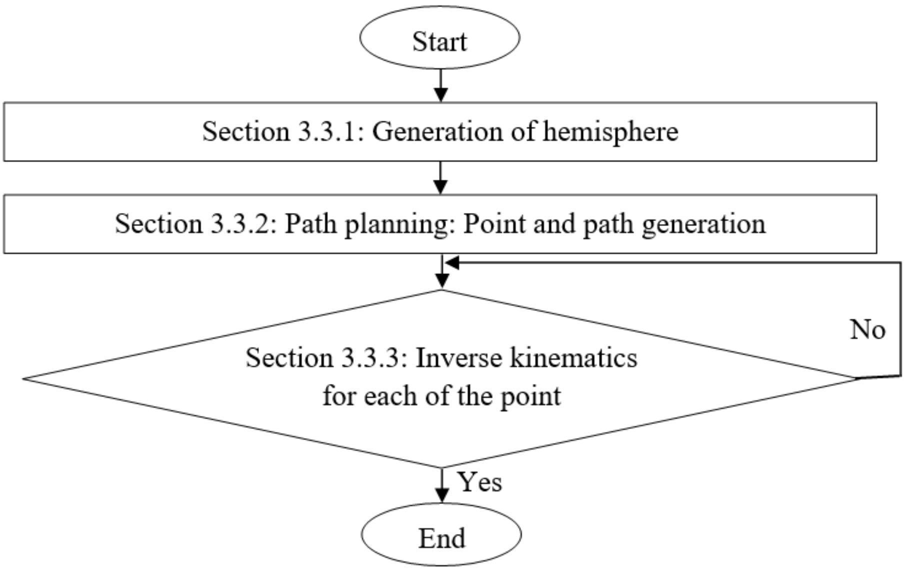

Figure 3.2: Theoretical background of the method flowchart

The main focus of this project was to maximize the point of view of the object by starting from the generation of hemisphere, then point generation, goes on to the path planning for path generation and end with the positioning the tip of the end effector of the robot manipulator while ensuring the webcam mounted on it was pointing toward the center point of the object. Based on Figure 3.2, theoretical background related to the generation of hemisphere, path planning in points and path generation, and inverse kinematics for each of the points are explained in this part.

3.3.1 Generation of hemisphere

Before points generation, forming a hemisphere that surrounded the center point of the hemisphere for the tip of the end effector of the robot manipulator to be facing toward is important in order for the points and the path of the points can be generated on the surface of it. For forming a hemisphere, Pythagoras' theorem will be used as shown in equation 3.1.

$$x^2 + y^2 + z^2 = r^2 \tag{3.1}$$

where (x, y, z) = coordinate on the surface of the hemisphere (m), and

r = radius of the hemisphere (m)

However, before applying the theorem, the position of the reference frame (0, 0, 0) of the robot manipulator needed to be known first. For this KUKA youBot, it is situated at the base center of the robot manipulator as shown in Figure 3.3 and all of the measurements will be based on the reference frame of the robot manipulator. After determining the center coordinate (x_c, y_c, z_c) of the hemisphere, the distance from the reference frame to the center coordinate of the hemisphere can be known. Then, with the center coordinate and radius of the hemisphere known, the formula as shown in equation 3.2 should be used.

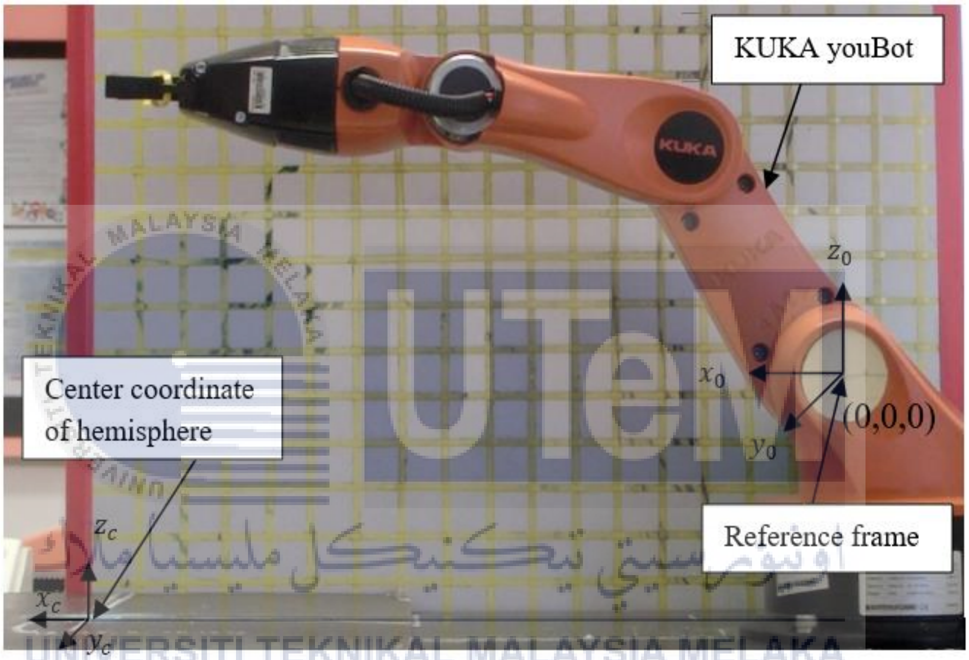

Figure 3.3: The position of the reference frame (0,0,0) of the KUKA youBot and the center coordinate (x_c, y_c, z_c) of the hemisphere

$$(x - x_c)^2 + (y - y_c)^2 + (z - z_c)^2 = r^2 \tag{3.2}$$

where (x_c, y_c, z_c) = center coordinate of the hemisphere (m)

After knowing the coordinate of the center of the hemisphere (x_c, y_c, z_c) and the radius of the hemisphere, a hemisphere will be formed as shown in Figure 3.4 by applying the formula in equation 3.2.

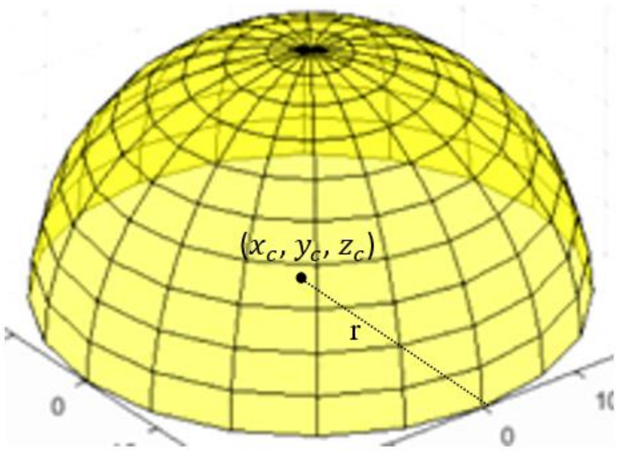

Figure 3.4: A hemisphere with its center point of (x_c, y_c, z_c) and radius, r

3.3.2 Path planning: Point and path generation

The path planning for maximizing the point of view of the object had divided into two parts, which were the point and path generation on the surface of the hemisphere. After the hemisphere is designed, generation of points on the surface of the hemisphere will be done first. In general, robot with any configuration can be applied for all of the points formed. However, for that case of this project, KUKA youBot is used but due to the reason that the KUKA youBot is operated without its mobile platform and its end effector could only move up and down, the generation of points will only be in vertical form instead of horizontal form. This is because if the points were in the horizontal form, the end effector of the KUKA youBot could move to that position, but it could not turned to face towards the center coordinate (x_c, y_c, z_c) of the hemisphere. This eventually causes the webcam that mounted on the tip of the KUKA youBot's end effector could not capture the video of the object that situated on the center point for the object. Therefore, the generation of points on the surface of the hemisphere will be done in vertical form for this research.

For the generation of points, a line of points is defined in spherical coordinates (r, θ, φ) first for setting a range for the points to be situated, and the points will then be converted to cartesian coordinates (x_p, y_p, z_p) by using the trigonometry function as shown in equation 3.3, 3.4 and 3.5 respectively.

$$x_p = r\cos\theta \tag{3.3}$$

$$y_p = r \tag{3.4}$$
$$z_p = r\sin\theta \tag{3.5}$$

Due to the reason that the points generated were in spherical coordinates, which centered with the coordinate of (0, 0, 0), the coordinate of the points needed to be translated by adding it with (x_c, y_c, z_c) as shown in equation (3.6), (3.7) and (3.8) respectively, in order for the points to be surrounded the hemisphere with its center point at (x_c, y_c, z_c). As for the path, it will eventually formed, where the point to be reached by the tip of the end effector of robot manipulator will started from the first point at the top of the line until the last point at the end of the line as shown in Figure 3.5.

$$x_p = x_p + x_c \tag{3.6}$$
$$y_p = y_p + y_c \tag{3.7}$$
$$z_p = z_p + z_c \tag{3.8}$$

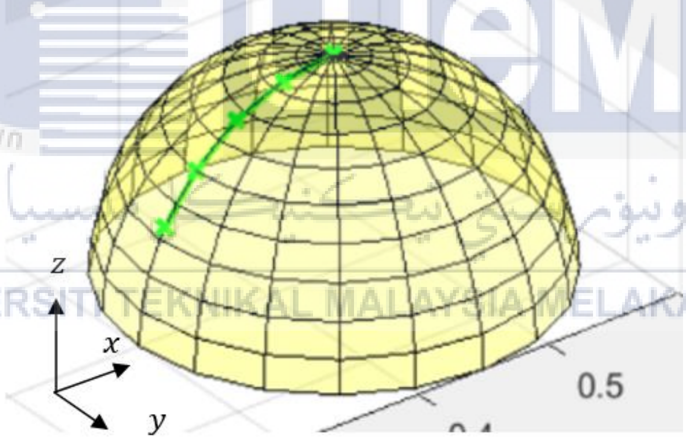

Figure 3.5: Path of points are generated on the surface of the hemisphere

3.3.3 Inverse kinematics for each of the point

Kinematics is the studies of a subject's motion without considerate the forces that causes it [8]. Inverse kinematics is the control of the robot manipulator by converting the position and orientation of its end effector from cartesian space to joint space, in order to obtain the joint values of each of the joint. In solving the inverse kinematics problem, there are some complications such as the existence of singularity problem and multiple solution for each of the coordinate [8]. In this research, after the generation of a path of points on the surface of the imaginary hemisphere, inverse kinematics will be used for directing the tip of the end effector of KUKA youBot to move to the generated points (x_p, y_p, z_p) and obtains the joint values of each of the joints. There are a total of 5 joints $(\theta_1, \theta_2, \theta_3, \theta_4, \theta_5)$ for this KUKA youBot, which the θ_5 for link 5 or joint value 4 will be constant with 3 radian, this is because a webcam will be situated on top of the tip of youBot's end effector, and the θ_1 for joint value 0 or base angle for link 1, it can be expressed using equation (3.9).

$$\theta_1 = tan^{-1}\frac{z_p}{x_p} \tag{3.9}$$

As for the arm comprising of link 2, link 3 and link 4 of the KUKA youBot as shown in Figure 3.6, the θ_2, θ_3, and θ_4 can be calculated using the equation from equation (3.10) to equation (3.23).

Figure 3.6: Link 2, link 3, and link 4 of the KUKA youBot with their respective joint angle of θ_2, θ_3, and θ_4

$$x_a = \sqrt{{x_p}^2 + {y_p}^2} \tag{3.10}$$

$$z_a = z_p \tag{3.11}$$

$$\phi_a = 0 \tag{3.12}$$

$$x_w = l_2 \sin(\theta_2) - (l_3 \times \sin(\theta_2 + \theta_3)) \tag{3.13}$$

$$z_w = l_2 \cos(\theta_2) - (l_3 \times \cos(\theta_2 + \theta_3)) \tag{3.14}$$

By simplifying the x_w and z_w in equation 3.13 and equation 3.14 respectively, equation 3.15 and 3.16 are formed.

$$x_w = x_a - (l_4 \times \cos(\phi_a)) \tag{3.15}$$
$$z_w = z_a - (l_4 \times (\phi_a)) \tag{3.16}$$

After that, equation 3.13 and 3.14 are squared and added for the both side of it and by simplifying the equation 3.16 using trigonometry function, equation 3.17 and 3.18 are formed for calculating θ_3 using equation 3.20.

$$cos\theta_3 = \frac{{l_2}^2 + {l_3}^2 - {x_w}^2 - {z_w}^2}{2(l_2)(l_3)} \tag{3.17}$$
$$sin\,\theta_3 = \sqrt{1 - \cos{\theta_2}^2} \tag{3.18}$$
$$\theta_3 = -(\,3.1416 - tan^{-1}\frac{sin\,\theta_3}{cos\theta_3}) \tag{3.19}$$

Then, by rewriting the equation 3.13 and 3.14, equation 3.20 is formed. Followed by using trigonometry function on the equation 3.20, equation 3.21 and 3.22 are formed to calculate the θ_2. As for the θ_4, it can be calculated by adding the θ_2 and θ_3.

$$k_1 = \frac{{l_2}^2 - {l_3}^2 + {x_w}^2 + {z_w}^2}{2(l_2)(\sqrt{{x_w}^2 + {z_w}^2})} \tag{3.20}$$
$$k_2 = \sqrt{1 - {k_1}^2} \tag{3.21}$$
$$\theta_2 = tan^{-1}\frac{z_w}{x_w} + tan^{-1}\frac{k_2}{k_1} \tag{3.22}$$

$$\theta_4 = \theta_2 + \theta_3 \tag{3.23}$$

Lastly, the joint value 1, joint value 2 and joint value 3 can be calculated as followed using equation 3.24, 3.25 and 3.26 respectively.

$$joint\ value\ 1 = 2.5988 - \theta_2 \tag{3.24}$$
$$joint\ value\ 2 = -2.4352 - \theta_3 \tag{3.25}$$
$$joint\ value\ 3 = 3.17859 + \theta_4 \tag{3.26}$$

Due to the reason that this project concerned for the KUKA youBot's joint 3, in order for the tip of its end effector to point toward the center of the hemisphere. The workspace of the KUKA youbot's joint 3 must took into account as shown in Figure 3.7.

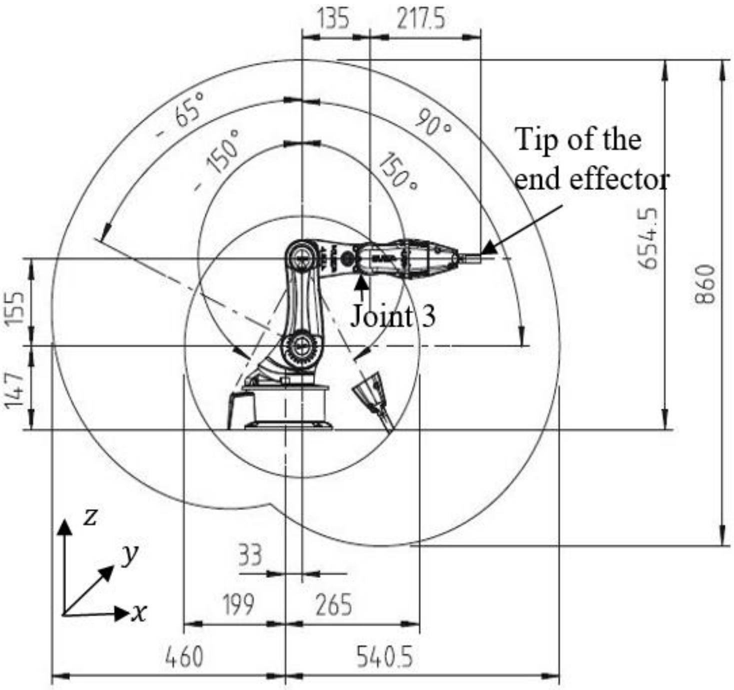

Figure 3.7: Workspace from KUKA youBot's sideview [22]

Based on Figure 3.7, it can be determined that the workspace for joint 3 to move is between -102.5° and 102.5°. With this joint limit, the limitation of the view by determining the joint 3 or the joint that is before the KUKA youBot's end effector can be determined to allow the tip of the its end effector to move towards the center point of the hemisphere. Therefore, when the tip of the end effector of the KUKA youBot has reached the points generated, the joint 3 for each of the points is needed to be changed in order for the tip of the youBot's end effector to point toward the center point of the hemisphere (x_c, y_c, z_c). With the condition that the joint 3 and the tip of the youBot's end effector is parallel in terms of y and z coordinate as shown in Figure 3.7, the θ that needed to be added to the joint 3 for the $(x_t\ , z_t)$ (i) of the tip of the youBot's end effector to move to $(x_t\ , z_t)$ (ii), can be calculated from equation 3.27 and 3.33 based on the Figure 3.8.

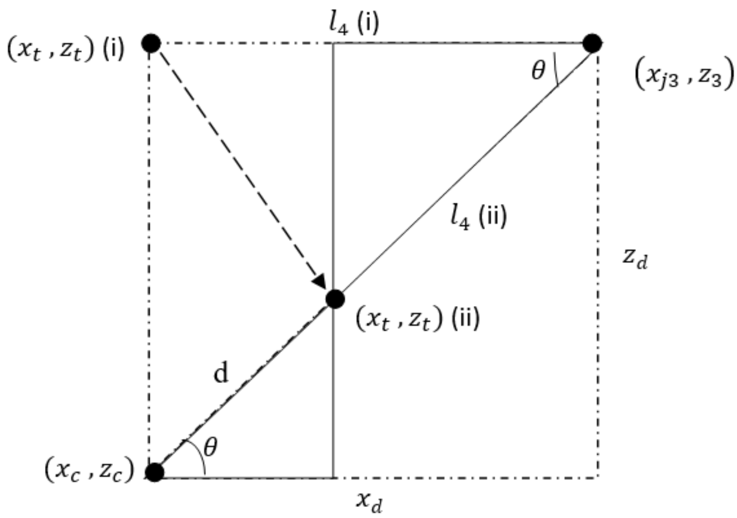

Figure 3.8: The relationship of x and z axis between the coordinate of the center point of the hemisphere (x_c, z_c), coordinate of the tip of the KUKA youBot's end effector (x_t, z_t), and the coordinate of the joint 3 of Kuka Youbot (x_{j3}, z_{j3})

Based on the Figure 3.8, coordinate (x_{j3}, z_{j3}) of the joint 3 needed to be known first by using equation 3.27. After that, by calculating the distance (x_d, z_d) between the (x_c, z_c) and (x_{j3}, z_{j3}), the additional angle, θ that required the joint 3 to turn is obtained by using the trigonometry function as shown in equation 3.28. Then, the distance, d between the tip of the end effector and the center point of the hemisphere can be calculated by using the equation 3.29.

$$(x_{j3}, z_{j3}) = (x_t - l_4, z_t) \tag{3.27}$$

$$\theta = \tan^{-1}\frac{z_d}{x_d} \tag{3.28}$$

$$d = \left(\sqrt{x_d{}^2 + z_d{}^2}\right) - l_4 \tag{3.29}$$

In order to get the actual coordinate of (x_t, z_t) (ii) of the tip of the KUKA youBot's end effector as shown in Figure 3.8, trigonometry function will be used as shown from equation 3.30 to equation 3.33.

$$\cos\theta = \frac{X}{d} \tag{3.30}$$

$$x_t = x_c - X \tag{3.31}$$

$$\sin\theta = \frac{Z}{d} \tag{3.32}$$

$$z_t = z_c - Z \tag{3.33}$$

After that, based on the distance, d from equation 3.29 and the distance, A between the webcam and the tip of the end effector of KUKA youBot, the actual coordinate (x_1, z_1) of the webcam that mounted on the tip of the end effector of KUKA youBot and the actual angle from the center point of the object to the position of the webcam can be calculated using the trigonometry function as shown from equation 3.34 to 3.40 based on the Figure 3.9. Also, the reference point of the object that should be captured by the webcam is also calculated using trigonometry function as shown from equation 3.41 to 3.45 based on the Figure 3.9.

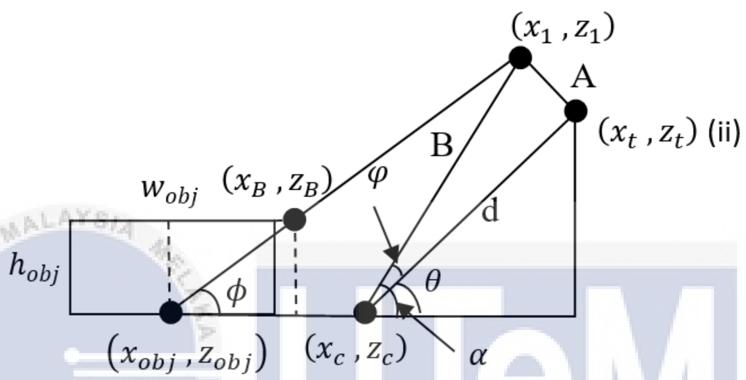

Figure 3.9: The relationship of x and z axis between the coordinate of the center point of the hemisphere (x_c, z_c), the coordinate of the tip of the KUKA youBot's end effector (x_t, z_t), the coordinate of the webcam that mounted on the tip of the end effector of KUKA youBot (x_1, z_1) and the coordinate of the center point of object (x_{obj}, z_{obj})

$$\mathrm{B} = \sqrt{A^2 + d^2} \tag{3.34}$$

$$\tan \varphi = \frac{B}{d} \tag{3.35}$$

$$\alpha = \theta + \varphi \tag{3.36}$$

When the angle between the center point of the hemisphere and the webcam that mounted on the tip of the end effector of KUKA youBot is obtained, the coordinate (x_1, z_1) of the webcam can be calculated as shown in equation 3.37 to equation 3.40.

$$\sin \alpha = \frac{Z_x}{A} \tag{3.37}$$

$$\therefore z_1 = z_c + Z_x \tag{3.38}$$

$$\cos \alpha = \frac{X_x}{A} \tag{3.39}$$

$$\therefore x_1 = x_c - X_x \tag{3.40}$$

After knowing the coordinate (x_1, z_1), the angle, ϕ between the center point of object and the webcam that mounted on the tip of the end effector of KUKA youBot can be calculated using equation 3.41. Then, by using the angle, ϕ obtained, the reference point (x_B, z_B) for the object that situated on the center point of the object (x_{obj}, z_{obj}) can be calculated using equation 3.42 to 3.45 .

$$\tan\phi = \left|\frac{z_{obj} - z_1}{x_{obj} - x_1}\right| \quad (3.41)$$

$$\tan\phi = \frac{h_{obj}}{X_g} \quad (3.42)$$

$$\therefore\ x_B = x_{obj} - X_g \quad (3.43)$$

$$\tan\phi = \frac{Z_g}{\frac{W_{obj}}{2}} \quad (3.44)$$

$$\therefore\ z_B = z_{obj} + Z_g \quad (3.45)$$

If the x_B is less than $(x_{obj} - \frac{W_{obj}}{2})$, equation 3.46 needed to be used in order to obtain the angle, γ between the center point of object (x_{obj}, z_{obj}) and the reference point for the object (x_B, z_B) first, then the reference line, z_F of the frame can be calculated using equation 3.48 as shown in Figure 3.10.

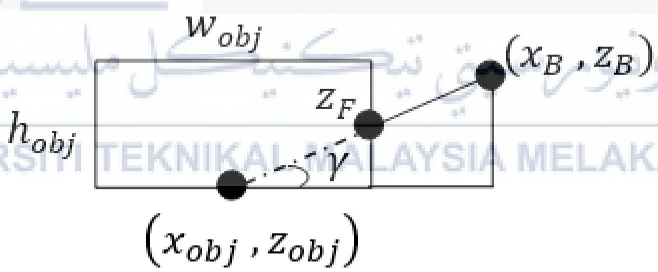

Figure 3.10: The relationship between the coordinate of the center point of the object (x_{obj}, z_{obj}), the coordinate of the reference point for the object (x_B, z_B), and the reference line of the frame, z_F

$$\tan\gamma = \left|\frac{z_{obj} - z_B}{x_{obj} - x_B}\right| \quad (3.46)$$

$$\tan\gamma = \frac{Z_u}{\frac{W_{obj}}{2}} \quad (3.47)$$

$$\therefore\ z_F = z_{obj} + Z_u \quad (3.48)$$

3.4 Research overview

The research methodology flowchart gives an insight of the method that will be done in this research as shown in Figure 3.11 below.

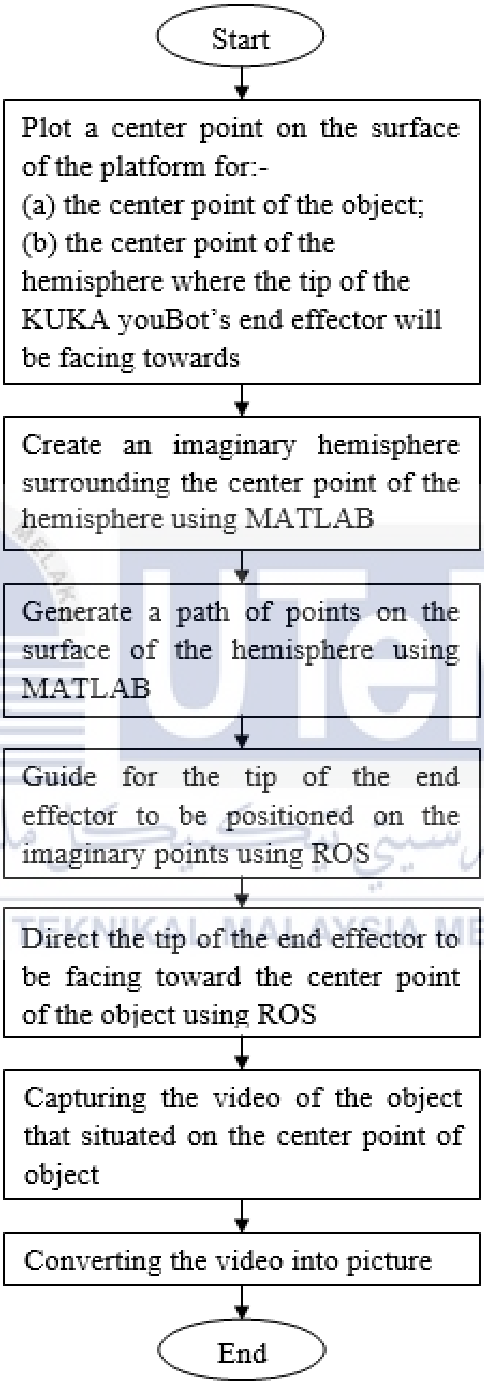

Figure 3.11: Research methodology flowchart

Based on the Figure 3.11, the center point of the object and center point of the hemisphere where the tip of the KUKA youBot's end effector will be facing towards are plotted first. After the center point of the hemisphere is known, an imaginary hemisphere surrounding the center point will be created using MATLAB. Then, points and path for the points are generated on the surface of the hemisphere using MATLAB too. When the coordinate of each of the points is known, the tip of the KUKA youBot's end effector is guided to be positioned on the points using ROS. After that, the tip of the end effector is directed to be facing towards the center point of the hemisphere. When the tip of the end effector is facing towards the center point of the hemisphere through all of the points, the KUKA youBot is run from the starting point until the ending point. While doing so, the video of the object that situated on the center point of the object are captured, which then the video will be converted into picture or frame.

3.5 Experiment setup

Figure 3.12 and Figure 3.13 have shown the experimental setup for this project with its equipment, axes and dimension stated in Table 3.1. In Figure 3.14, the size of the tested object is also shown. For Figure 3.12, it has shown the side view of the project, where a camera is fixed in a distance for capturing the process of the experiment. Meanwhile, Figure 3.13 has shown the front and close view of the project, where the movement of the KUKA youBot took place.

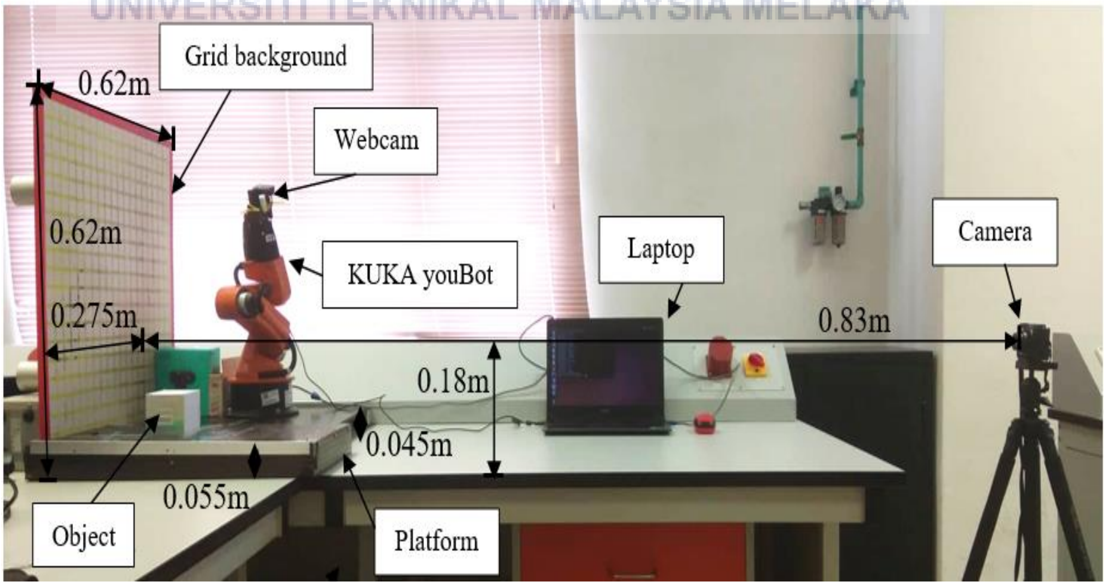

Figure 3.12: Side view of the experimental setup

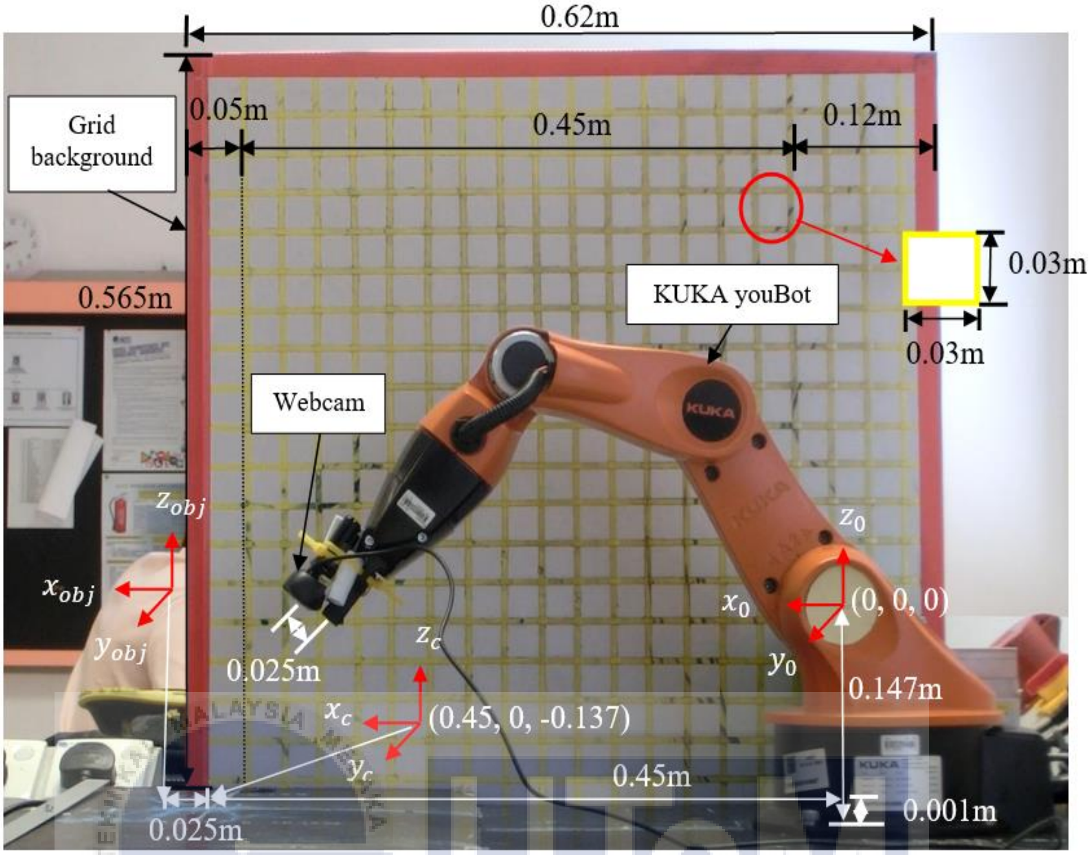

Figure 3.13: Front view of the experimental setup

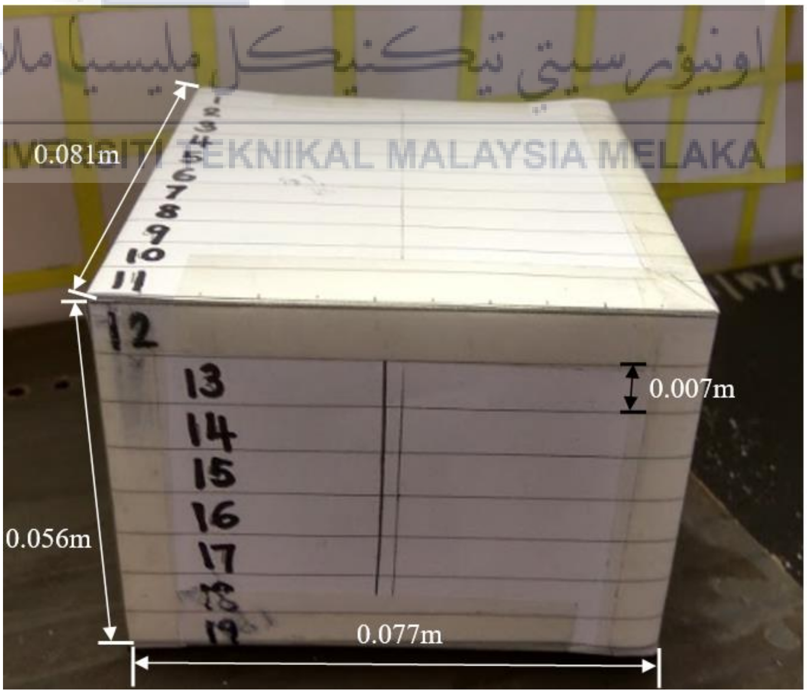

Figure 3.14: The size of the tested object with 19 and a half lines

Figure 3.15: Top view of the tested object with its coordinate x_B when it is situated on the center point of the object $(x_{obj,}\ z_{obj})$

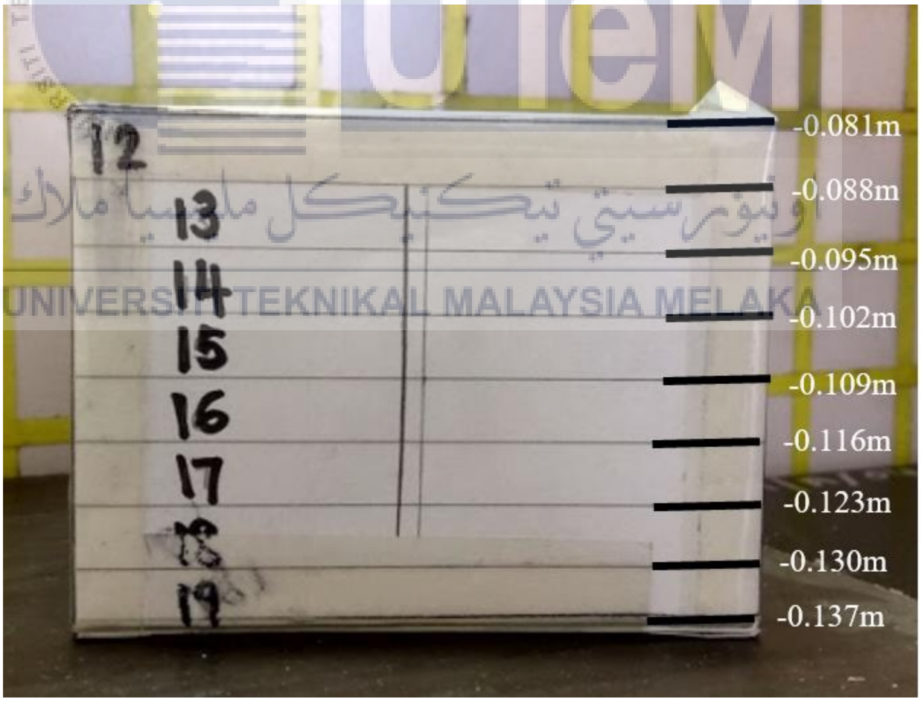

Figure 3.16: Front view of the tested object with its coordinate z_B when it is situated on the center point of the object $(x_{obj,}\ z_{obj})$

Table 3.1: Variables for the experimental setup

No.	Variable	Value	Unit
1	Distance from the grid background to the camera	(0.275, 0.83, 0.18)	m
2	Height of the KUKA youBot’s platform	0.045	m
3	Height of the platform for center point of hemisphere and center point of object	0.055	m
4	Area of the grid background	0.62 x 0.62	m^2
4	Area of one grid in the grid background	0.03 x 0.03	m^2
5	Coordinate of the center point of the imaginary hemisphere where the tip of the end effector needed to be facing toward	(0.450, 0, -0.137)	m
6	Coordinate of the reference point of the KUKA youBot	(0, 0, 0)	m
7	Coordinate of the center point of the object where the webcam is facing toward	(0.475, 0, -0.137)	m
8	Distance between the webcam and the tip of the KUKA youBot’s end effector	0.025	m
9	Webcam pixel	720	pixel
10	Volume of the object to be tested	0.077 x 0.081 x 0.056	m^3
11	The distance between each of the line on the surface of the tested object	0.007	m

Based on Table 3.1, the area of the grid background and area of one grid in the grid background are 0.62m x 0.62m and 0.03m x 0.03m respectively. The reference frame of the KUKA youBot with coordinate of (0, 0, 0) will be situated on the position as shown in Figure 3.13, and every measurement for the coordinate will be based from the reference frame.

The platform for the object to be tested is 0.001m higher than the KUKA youBot’s platform and the x-coordinate distance will be 0.45m difference between the reference point and center point of the imaginary hemisphere and 0.475m difference between the reference point and the center point of the object. Thus, the coordinate for the center point of the imaginary hemisphere where the tip of youBot’s end effector needed to be facing toward is (0.45, 0, -0.137)m and the coordinate for the center point of object is (0.475, 0, -0.137)m.

The distance between the webcam with 720 pixel and the tip of the end effector of KUKA youBot is 0.025m. A camera that located at a distance of (0.275, 0.83, 0.18)m away from the grid background will be used to capture the process of the experiment. Next, based on Figure 3.14, an object with the volume of 0.077m x

0.081m x 0.056m will be tested in this project. Its coordinate x_B and z_B when situated on the center point of the object $(x_{obj,}\, z_{obj})$ are shown in Figure 3.5 and Figure 3.6 respectively.

3.5.1 Materials/ equipment used

The materials or equipment that will be used in this project are:-

- KUKA youBot
- Webcam
- MATLAB software
- ROS Indigo software
- Measuring tape
- Protractor
- Camera
- An object to be tested

3.5.1.1 KUKA youBot

KUKA youBot is a robot manipulator which used for engineering practices and researches. This robotic arm consists of five joints with five degree of freedoms that can be programmed using open source software such as ROS. It has the height of 655mm and weight of 5.3kg [22]. It made by magnesium cast and communicates through EtherCAT. The youBot arm dimension and working range for each of the joint of the KUKA youBot are shown in the Figure 3.17.

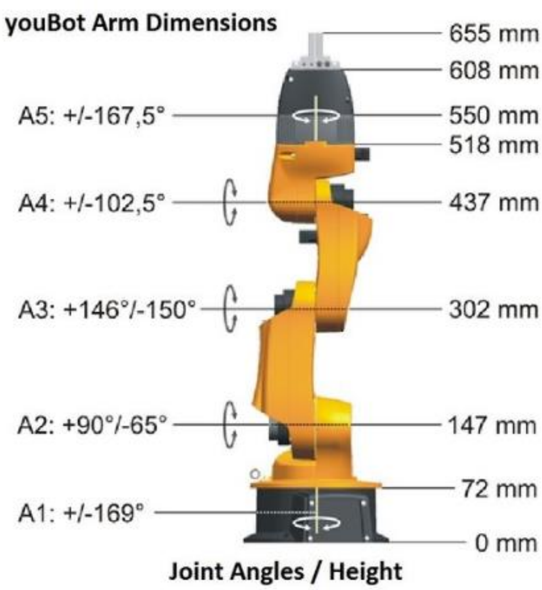

Figure 3.17: YouBot arm dimension and working range for each of the joint of KUKA YouBot [22]

The workspace of the KUKA youBot that looks from the side view is shown in Figure 3.18.

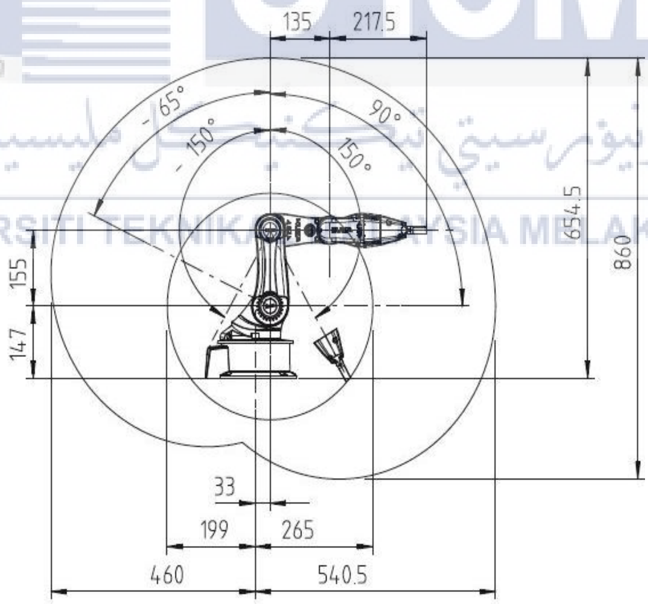

Figure 3.18: Workspace from KUKA youBot's sideview [22]

The workspace of the KUKA youBot that looks from the top view is shown in Figure 3.19. Based on the Figure 3.19, it indicates that this youBot manipulator can only rotates 170° clockwise and counter clockwise.

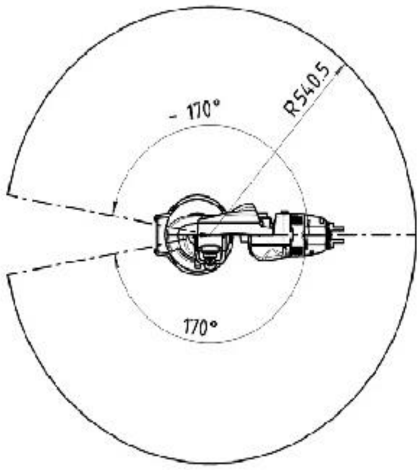

Figure 3.19: Workspace from KUKA youBot's top view [22]

In addition with this robot manipulator, a webcam will be mounted on the tip of the KUKA youBot's end effector, in order for the system to operate conveniently and faster.

3.5.1.2 Webcam

A webcam is a camera that can capture image in real time through or to a computer with their contrast and colourful image captured [23]. In order for ensuring the webcam is moving to the correct position given and the webcam is facing towards the center point of the object to capture the video of the object from point to point accurately, a webcam is needed by mounted it on the tip of the end effector of the KUKA youBot.

Figure 3.20: Logitech C310 HD Webcam [23]

Based on Figure 3.20, it is a Logitech C310 HD webcam, which has a fixed, standard HD lens with its resolutions goes up to 720 pixels and 60° field of view. In addition, this webcam can adjusts according to the surrounding lighting conditions in order to provide a more contrast and bright image of the object [23]. Therefore, it will be chosen to be used for this project by capturing the video of the object when the webcam that mounted on the tip of robot manipulator's end effector goes from one point to another point on the surface of the hemisphere while ensuring the webcam is facing towards the center point of the object. After the video is captured, image or frame will be extracted to analyze the coverage of the object.

3.5.1.3 MATLAB software

MATLAB is the mathematical computing software developed by MathWorks. It is used for creating 3D models, developing algorithms and analyzing data [24]. Due to this, it is chosen for this project for creating an imaginary hemisphere, and generating points and path of points on the surface of the hemisphere.

3.5.1.4 ROS (Robot Operating System) Indigo software

ROS (Robot Operating System) Indigo is an open-source platform, which it serves as an operating system for the KUKA youBot. It is designed based on a complex mobile platform containing sensors, robotic hands, grippers and others [25]. Thus, it will be chosen to use for this project by connecting it to the KUKA youBot with the webcam mounted on the tip of its end effector.

3.5.1.5 Measuring tape

Measuring tape is a common measuring tool that uses to measure the distance between the objects or the length of the object. In this particular project, the measuring tape as shown in Figure 3.21 will be used for setting up the experiment of this project. The distance between the reference frame of the KUKA youBot and the center point of the object, as well as the center point of the hemisphere are measured using the measuring tape. The area of the grid background and the distance for the camera to be fixed away from the grid background are also measured using measuring tape. This same goes to the distance between the tip of the KUKA youBot's end effector and the webcam that needed to be mounted on it.

Figure 3.21: Measuring tape

3.6 Experiment

In this project, there are 3 experiments that needed to be conducted in order to fulfill the objectives of this project. The 3 experiments have included of (1) study on the percentage of error based on the proposed method in generation of points and path on the surface of the hemisphere for the tip of the end effector of KUKA youBot to be positioned, (2) study on the validity of the proposed method in directing the tip of the end effector of KUKA youBot to face toward the center point of the hemisphere, and (3) study on the validity of the proposed method in directing the webcam mounted on the tip of the end effector of KUKA youBot to face toward the center point of the object.

3.6.1 Experiment 1: Study on the percentage of error based on the proposed method in generation of points and path on the surface of the hemisphere for the tip of the end effector of KUKA youBot to be positioned

3.6.1.1 Objectives

The objectives of this experiment are:-

- To construct an imaginary hemisphere surrounding the center point of the hemisphere where the tip of the KUKA youBot's end effector will be pointing toward
- To generate points and path on the surface of the imaginary hemisphere

- To analyze the position of the tip of the end effector of the KUKA youBot in term of x-coordinate and z-coordinate

3.6.1.2 Materials/ equipment used

The materials/equipment that needed to be used for this experiment are:-

- MATLAB software
- ROS Indigo software
- KUKA youBot
- Camera

3.6.1.3 Procedure

1. An imaginary hemisphere with its center point of (0.45, 0, -0.137)m and radius of 0.287m is formed.
2. The line of elevation is set in the range from 90° to 60° and the line of the azimuth is set to 180°.
3. 5 points are generated within the line of elevation and azimuth in spherical coordinates.
4. The 5 points are then converted to cartesian coordinates (x_p, y_p, z_p).
5. A path of the points is formed with the starting coordinate (point 1) at 90° and the ending coordinate (point 5) at 60° from the center point of the imaginary hemisphere.
6. The coordinate of the points from point 1 to point 5 is recorded and tabulated in Table 4.1.
7. The coordinates of the points are inserted into the coding of inverse kinematics, ROS Indigo software is run and the movement of the KUKA youBot is recorded using the camera.
8. The joint values of each of the joints from point 1 to point 5 are recorded in Table 4.2.
9. The recorded video is then extracted to frames.

10. The coordinate of the tip of the end effector of KUKA youBot (x_t, z_t) is measured, recorded and compared with the actual points' coordinate (x_p, z_p) in Table 4.3.

3.6.2 Experiment 2: Study on the validity of the proposed method in directing the tip of the end effector of KUKA youBot to face toward the center point of the hemisphere

3.6.2.1 Objectives

The objectives of this experiment are:-

- To direct the tip of the end effector of KUKA youBot to face toward the center point of the imaginary hemisphere
- To analyze the angle between the joint 3 of the KUKA youBot and the center point of the imaginary hemisphere
- To analyze the position of the tip of the end effector of KUKA youBot in term of x-coordinate and z-coordinate

3.6.2.2 Materials/ equipment used

The materials/ equipment that needed to be used for this experiment are:-

- ROS Indigo software
- KUKA youBot
- Camera
- Protractor

3.6.2.3 Procedures

1. The angle of joint 3 of the KUKA youBot is added with the calculated angle from equation 3.28 and the joint values of each of the joints from point 1 to point 5 are recorded in Table 4.4.
2. The ROS Indigo software is run and the movement of the KUKA youBot is recorded using the camera.
3. The frames are then extracted from the recorded video.

4. Based on the frames collected, the angle between the position of joint 3 of KUKA youBot from the center point of the imaginary hemisphere is measured, recorded and compared with the calculated angle for each of the point in Table 4.5.
5. Then, the coordinate of the tip of the end effector of KUKA youBot (x_t, z_t) for each of the point is also measured, recorded and compared with the actual calculated points' coordinate (x_t, z_t) in Table 4.6.

3.6.3 Experiment 3: Study on the validity of the proposed method in directing the webcam mounted on the tip of the end effector of KUKA youBot to face toward the center point of the object

3.6.3.1 Objectives

The objective of this experiment is:-

- To analyze the reference line of the frame captured by the webcam that mounted on the tip of the end effector of KUKA youBot from one point to another point

3.6.3.2 Materials/ equipment used

The materials/ equipment that needed to be used for this experiment are:-

- ROS Indigo software
- KUKA youBot
- Webcam
- An object to be tested

3.6.3.3 Procedures

1. The object to be tested is situated at the center point for the object.
2. While the webcam that mounted on the tip of the end effector of KUKA youBot is moved from one point to another point, video of the object is captured and saved.

3. The frame of the object taken by the webcam for each of the point is extracted from the video.
4. The reference line, z_F that situated at the center of the frame is drawn, measured, recorded and compared with the actual reference line, z_F in Table 4.7.

3.7 Method for analysis

3.7.1 Percentage of error

Percentage of error is a measure of how big the errors are obtained from the experiment. For this project, percentage of error will be used to determine the error between the actual angle and measured angle of the KUKA youBot's joint 3 from the center point of the hemisphere using equation 3.49 and the error between the actual coordinate and measured coordinate of the tip of the end effector of KUKA youBot will be calculated using the percentage of position error in equation 3.50. Not only that, percentage of error will also be used to determine the error between the actual reference line and measured reference line of the webcam that mounted on the tip of the end effector of KUKA youBot toward the frame captured using equation 3.49. After that, the validity of the proposed method can be determined based on the calculated percentage of error and percentage of position error.

$$\text{Percentage of error } (\%) = \frac{|\text{measured value} - \text{actual value}|}{\text{actual value}} \text{ x } 100\% \tag{3.49}$$

$$\text{Percentage of position error } (\%) = \sqrt{(\text{Actual x} - \text{measured x})^2 + (\text{Actual z} - \text{measured z})^2} \tag{3.50}$$

3.8 Reliability of the data

For plotting the coordinate of the center point of the hemisphere and the center point of the object, the distance between them from the reference point of the KUKA youBot is measured using the measuring tape. As for the capturing the process of the movement of the robot manipulator, the camera must be faced toward the grid coordinator and the distance between them is also measured using the measuring tape. All in all, when doing the measurement, the eye must be placed at 90° to the level of the measurement on the measuring tape to avoid parallax error.

For the percentage of position error for the coordinate of the tip of the end effector of the robot manipulator and coordinate of the webcam that mounted on the tip of the end effector of KUKA youBot at each of the point, and the percentage of error for the angle between the position of joint 3 and the position of the center of hemisphere, and the reference line of the frame for the webcam mounted on the tip of the end effector of KUKA youBot to look at, the errors obtained might be affected by factors such as the uncertainties in making the measured variables when the position to be measured is located between the lines or the reference line drawn is not on the exact point.

3.9 Summary of the chapter

This chapter presents the proposed methodology in order to develop a new, effective project. The theoretical background of the methods that will be used in this project is explained with illustrations and equations given. Project methodology and research overview of this project are explained with the flowchart given. Then, experiment setup is described with the coordinates and axes stated, and materials or equipment that will be used for this project are also explained with their functionality. Experiments that will be conducted for this project of path planning for maximizing the point of view of an object using the robotic arm with vision are also explained with their respective objectives, materials or equipment used and procedures. After that, methods for analyzing the experiments are also described, which have included of percentage of error and percentage of position error. Lastly, the reliability of the data is also explained in this chapter in order for the measurements or data collected from the experiments are accurate. Therefore, this chapter is very important to ensure that all of the objectives of this project are able to be achieved successfully.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, the results that obtained from the MATLAB software and the movement of the KUKA youBot from the ROS Indigo software will be presented based on the experiments done.

4.2 Result and analysis

4.2.1 Experiment 1: Study on the percentage of position error based on the proposed method in generation of points and path on the surface of the hemisphere for the tip of the end effector of KUKA youBot to be positioned

Based on the result obtained from the MATLAB software, a path of 5 points are generated on the surface of the imaginary hemisphere as shown in Figure 4.1, and the coordinate for each of the points (x_p, y_p, z_p) is obtained and recorded in Table 4.1.

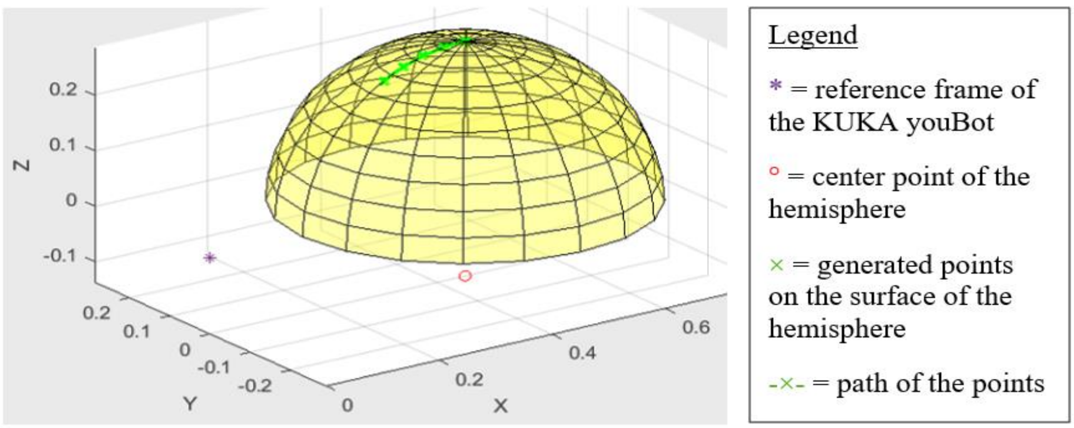

Figure 4.1: The imaginary hemisphere with the path of 5 points generated on the surface of it

Based on the Figure 4.1, the reference frame of the KUKA youBot is at (0, 0, 0)m, where the measurements of all of the coordinate will based on this point. Then, in the Figure 4.1, a hemisphere with the center point of (0.45, 0, -0.137)m and radius of 0.287m is formed. A total of 5 points are generated on the surface of the hemisphere, which then a path for the 5 points are generated, which point 1 is the initial point at 90° and point 5 is the final point at 60° from the center point of the hemisphere as shown in Figure 4.1. The coordinate (x_p, y_p, z_p) for each of the points are then recorded as shown in the Table 4.1.

Table 4.1: The coordinate (x_p, y_p, z_p) of the 5 points generated on the surface of hemisphere

Point \ Coordinate	x_p (m)	y_p (m)	z_p (m)
1	0.4500	0	0.1500
2	0.4125	0	0.1475
3	0.3757	0	0.1402
4	0.3402	0	01282
5	0.3065	0	0.1115

After the coordinate for each of the points are obtained as shown in Table 4.1, the coordinate of (x_p, y_p, z_p) for each of the points are inserted to the inverse kinematic code in ROS Indigo software in order to move the tip of the end effector of KUKA youBot to be positioned on the points generated and to obtain the joint values for each of the points as shown in Table 4.2. After that, the video for the movement of the KUKA youBot that captured from the camera is extracted into frames for the 5 points. Starting from point 1 to point 5, each of the point is measured based on the grid at the grid background as shown in Figure 4.2.

Table 4.2: Joint values for the 5 points obtained from inverse kinematics

Joint Value \ Point	1	2	3	4	5
Joint 0 (radian)	2.9624	2.9624	2.9624	2.9624	2.9624
Joint 1 (radian)	1.73719	1.42249	1.1791	0.962276	0.759955
Joint 2 (radian)	-1.81574	-1.29152	-0.918792	-0.601351	-0.311281
Joint 3 (radian)	1.97394	1.76443	1.63509	1.53448	1.44673
Joint 4 (radian)	3	3	3	3	3

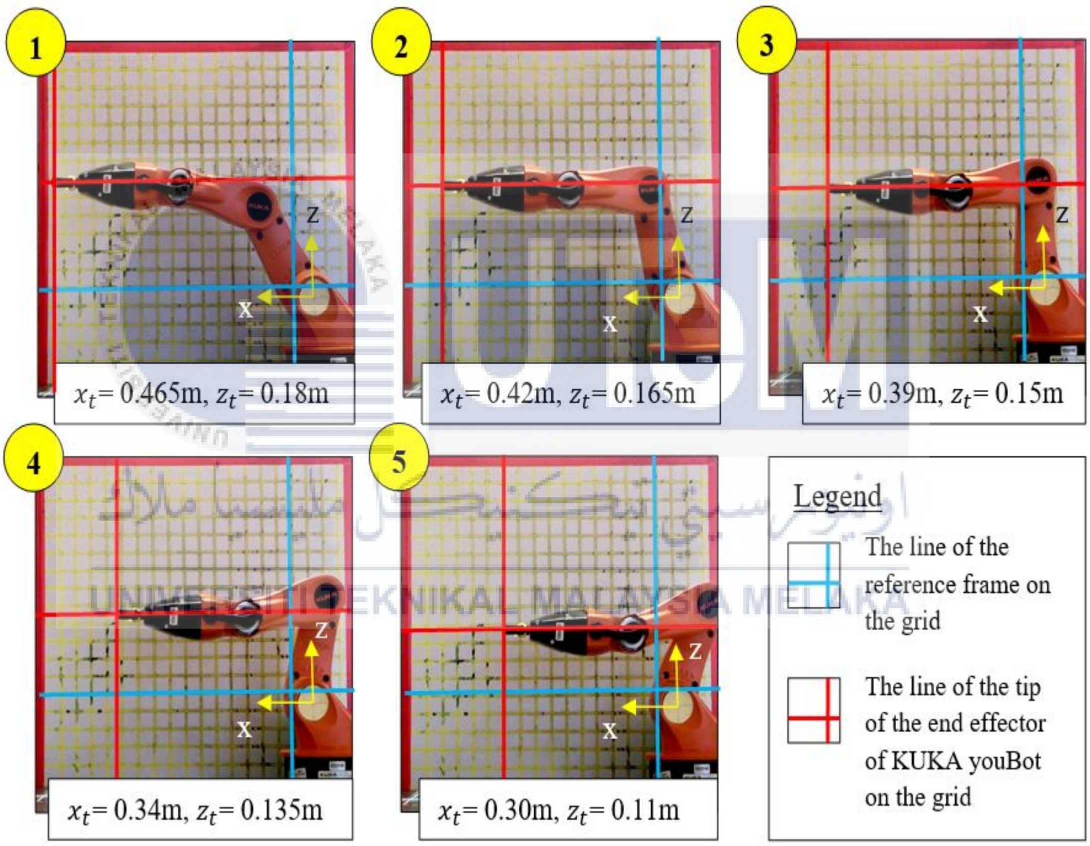

Figure 4.2: The measured coordinate (x_t, z_t) of the tip of the end effector of KUKA youBot based on the reference frame (0, 0)

Based on the data in Figure 4.2, the measured coordinate (x_t, z_t) of the tip of the end effector of KUKA youBot will then compared with the actual coordinate (x_p, z_p) by calculating the difference between their x and z coordinate and the percentage of position error as shown in Table 4.3. After that, the graph for the path of the points formed by the actual coordinates and the measured coordinates of the tip of the end effector of KUKA youBot are shown in Figure 4.3.

Table 4.3: The difference between the x and z coordinate, and the percentage of position error between the actual coordinate (x_p, z_p) and measured coordinate (x_t, z_t) of the tip of the end effector of KUKA youBot

Coordinate / Point	Actual coordinate (m)		Measured coordinate (m)		Difference between x coordinate (m)	Difference between z coordinate (m)	Percentage of position error (%)
	x_p	z_p	x_t	z_t			
1	0.4500	0.1500	0.465	0.180	0.0150	0.0300	3.35
2	0.4125	0.1475	0.420	0.165	0.0075	0.0175	1.90
3	0.3757	0.1402	0.390	0.150	0.0143	0.0098	1.73
4	0.3402	0.1282	0.340	0.135	0.0002	0.0068	0.68
5	0.3065	0.1115	0.300	0.110	0.0065	0.0015	0.67
Average difference (m)					0.0087	0.0656	-
Average percentage of position error (%)					-	-	1.67

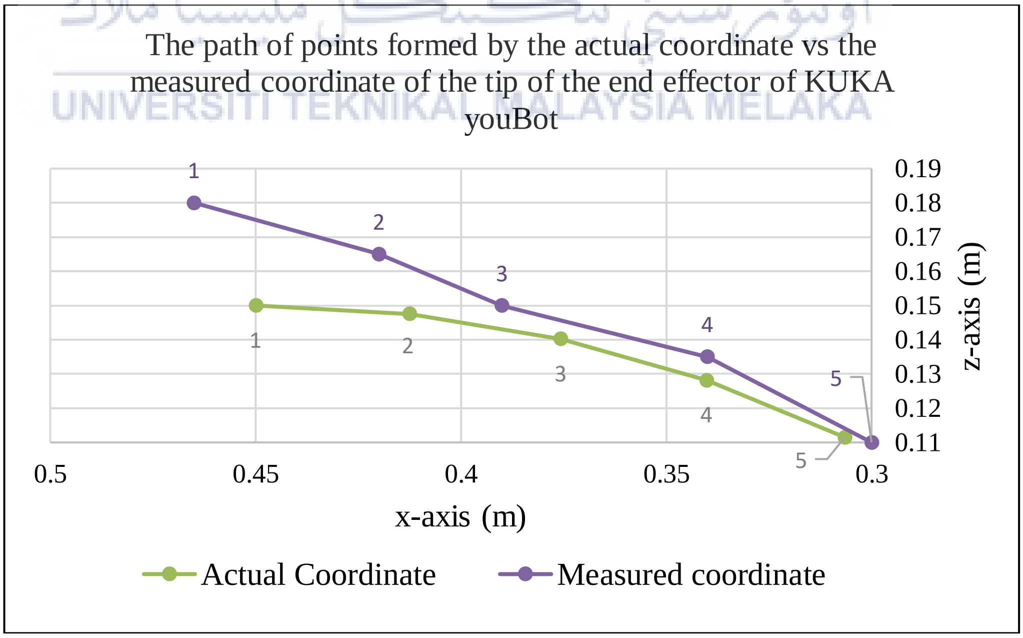

Figure 4.3: Graph of the path of points formed by the actual coordinate and the measured coordinate of the tip of the end effector of KUKA youBot

Based on the joint values for each of the point as shown in Table 4.2, the tip of the end effector of KUKA youBot is always pointing forward to the x-axis, while not facing toward the center point of the object as shown in Figure 4.2. Then, based on Table 4.3, the average difference between the actual coordinate and the measured coordinate for x-coordinate and z-coordinate are 0.0087m and 0.0656m respectively. Meanwhile, the average percentage of position error between the actual coordinate and measured coordinate of the tip of the end effector of KUKA youBot is only 1.67%.

From the Figure 4.3, it can be seen that the coordinate of point 1 between the actual coordinate and measured coordinate has the difference of 0.015m and 0.03m for x and z coordinate respectively, this slightly big difference between the actual and measured coordinate of the tip of the end effector of the youBot was because when the arm of the KUKA youBot is stretched out from its initial state to point 1, there is an acceleration in the arm and caused jerk, due to the reason that point 1 is further away from the initial position and it needed to complete its action in the time given. However, based on Table 4.3 and Figure 4.3, the difference between the actual coordinate and measured coordinate can be seen that it was getting smaller from point to point, which point 5 has the most less difference between the coordinates with its percentage of position error of 0.67% only.

Although the tip of the end effector of KUKA youBot did not move in a curve pattern as planned, but its average difference between the actual coordinate is very little with the error of 1.67%, which the youBot behaved very close to what it was expected in the path planning. Thus, it can be said that the proposed method is valid, because the tip of the end effector of KUKA youBot is positioned on the path of points with x and z coordinate of the actual coordinate and measured coordinate lesser than 0.01m and it has an average percentage of position error of 1.67% only.

4.2.2 Experiment 2: : Study on the validity of the proposed method in directing the tip of the end effector of KUKA youBot to face toward the center point of the hemisphere

After calculated the angle that needed to be added to the angle of joint 3, the joint value of joint 3 is changed as shown in Table 4.4.

Table 4.4: Joint values for the 5 points obtained from inverse kinematics after the addition of angle to the joint 3

Point / Joint Value	1	2	3	4	5
Joint 0 (radian)	2.9624	2.9624	2.9624	2.9624	2.9624
Joint 1 (radian)	1.73719	1.42249	1.1791	0.962276	0.759955
Joint 2 (radian)	-1.81574	-1.29152	-0.918792	-0.601351	-0.311281
Joint 3 (radian)	2.89514	2.60353	2.39399	2.21438	2.04873
Joint 4 (radian)	3	3	3	3	3

Then, in order to calculate the percentage of error between the actual angle and the measured angle from the center point of hemisphere towards the position of youBot's joint 3, the frame of the movement of KUKA youBot going from one point to another point is captured and the angle between them is measured as shown in Figure 4.4. The result is then tabulated in a table and graph as shown in Table 4.5 and Figure 4.5 respectively, for comparing the difference between the actual angle and measured angle from the center point of the hemisphere towards the position of KUKA youBot's joint 3.

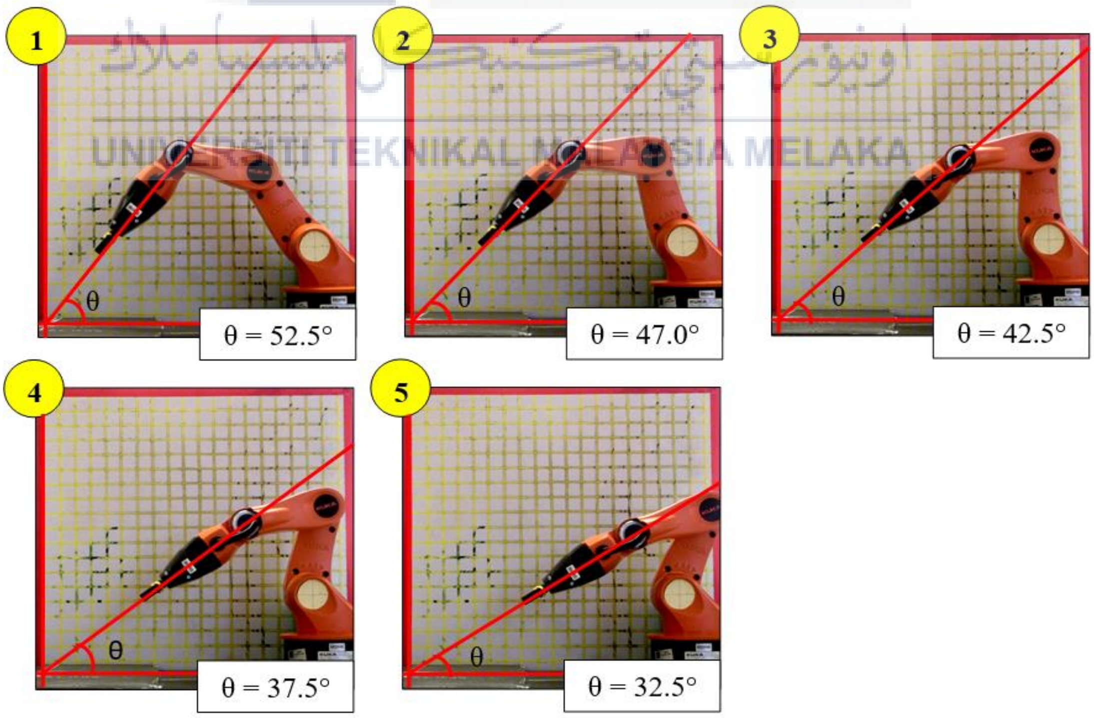

Figure 4.4: Measured angle, θ from the center point of the hemisphere towards the position of the youBot's joint 3 from point 1 to point 5

Table 4.5: The percentage of error between the actual angle and measured angle from the center point of the hemisphere towards the position of the youBot's joint 3 from point 1 to point 5

Point	Actual angle (°)	Measured angle (°)	Percentage of error (%)
1	52.78	52.50	0.53
2	48.08	47.00	2.25
3	43.48	42.50	2.25
4	38.96	37.50	3.75
5	34.49	32.50	5.77
Average percentage of error (%)			2.91

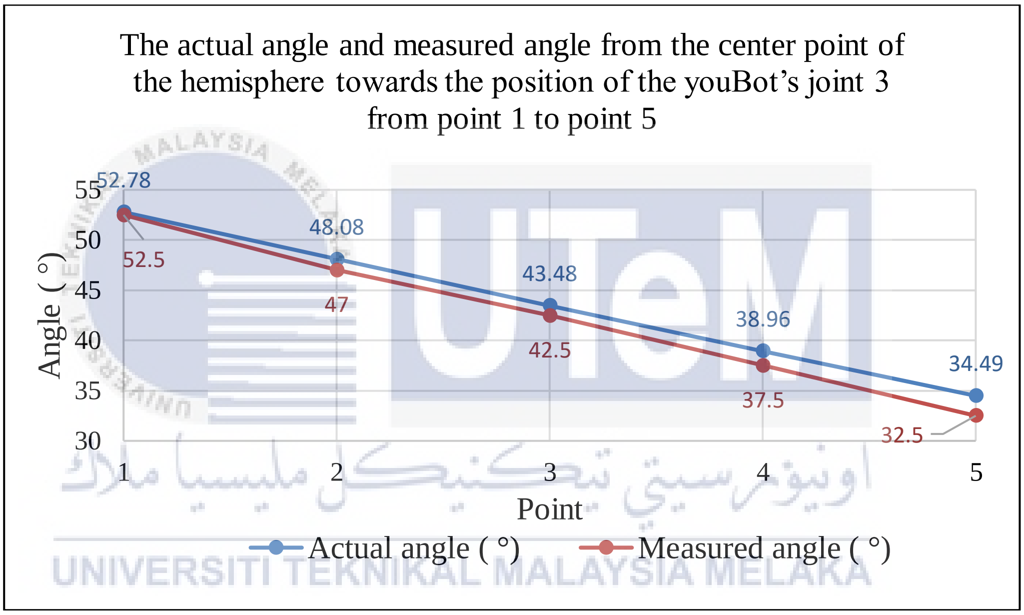

Figure 4.5: Graph of the actual angle and measured angle from the center point of the hemisphere towards the position of the youBot's joint 3 from point 1 to point 5

Based on the Figure 4.4, with the changing of joint 3 value as shown in Table 4.4, the tip of the end effector of KUKA youBot able to point toward the center of the hemisphere. Then, based on the Table 4.5, the percentage of error for the angle from the center point of hemisphere to the position of joint 3 is getting bigger through the path from the initial point to final point. This has indicated that the smaller the angle between the position of the youBot's joint 3 and the center point of the hemisphere, the bigger the percentage of error. However, for this project, the percentage of error between the actual angle and measured angle is still very small as shown in Figure 4.5, with its average percentage of error of 2.91%.

As for the measured coordinate (x_t, z_t) of the tip of the end effector of KUKA youBot through the sequence of points, from point 1 to point 5, it is measured based on the grid background at the back and the KUKA youBot's reference frame as shown in Figure 4.6. The measured coordinate is then recorded, tabulated and compared with the actual coordinate for the tip of the end effector of KUKA youBot to be positioned by calculating the difference between their x and z coordinate and the percentage of position error as shown in Table 4.6.

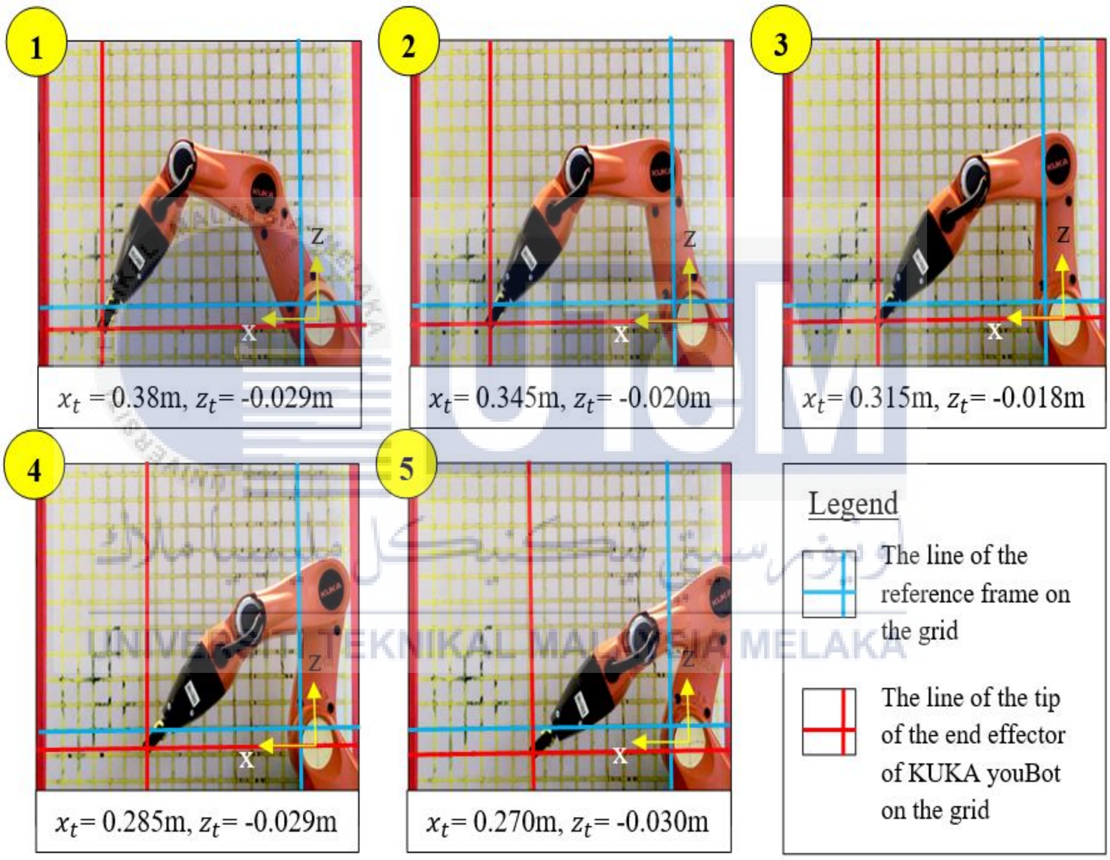

Figure 4.6: The measured coordinate (x_t, z_t) of the tip of the end effector of KUKA youBot after changing the joint value of KUKA youBot's joint 3 from point 1 to point 5

Table 4.6: The difference between the x and z coordinate, and the percentage of error between the actual coordinate and measured coordinate of the tip of the end effector of KUKA youBot after changing the joint value of youBot's joint 3

Coordinate / Point	Actual coordinate (m)		Measured coordinate (m)		Difference between x coordinate (m)	Difference between z coordinate (m)	Percentage of position error (%)
	x_t	z_t	x_t	z_t			
1	0.364	-0.024	0.380	-0.029	0.016	0.004	1.6
2	0.340	-0.015	0.345	-0.020	0.005	0.005	0.7
3	0.316	-0.010	0.315	-0.018	0.001	0.008	0.8
4	0.291	-0.009	0.285	-0.029	0.006	0.020	2.1
5	0.268	-0.012	0.270	-0.030	0.002	0.018	1.8
Average difference (m)					0.006	0.011	-
Average percentage of position error (%)					-	-	1.4

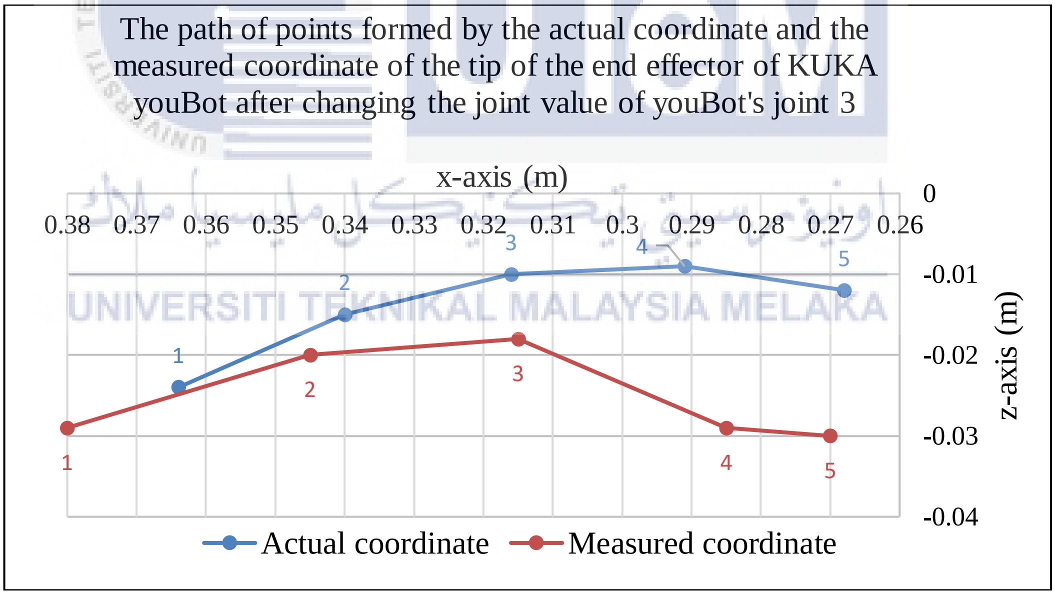

Figure 4.7: Graph of the path of points formed by the actual coordinate and the measured coordinate of the tip of the end effector of KUKA youBot after changing the joint value of youBot's joint 3

Based on the Figure 4.7, the path of points from the actual coordinate for the tip of the end effector of KUKA youBot to be positioned from the initial point 1 to the final point 5 is in a slightly curvy pattern, while the path of points formed from the measured coordinate has shown a not so stable movement, with the movement of the tip of the end effector of KUKA youBot moved to a higher position until point 3, then back to a lower position to point 5. This eventually has related to the percentage of error for the angle from the center point of hemisphere to the position of joint 3, which is getting bigger through the path as shown in Figure 4.5. However, from the Table 4.6, it can be seen that the difference between the x-coordinate and the z-coordinate of the measured coordinate and actual coordinate is 0.006m and 0.011m respectively. This has shown that the difference between the actual coordinate and measured coordinate is very small with an average percentage of position error of 1.4% only.

Not only that, based on Figure 4.7, it also can be seen that there is a slight difference in x and z coordinate for point 1, it was due to the acceleration of the arm to stretch out within the given time. Then, when the arm goes to point 4 and point 5, the difference in x and z coordinate were getting bigger because with the increasing distance of the tip of the end effector of the KUKA youBot from the center point of the hemisphere, the position error for the points will also increasing [26]. Therefore, the difference in x and z coordinate between the actual coordinate and measured coordinate for point 4 and 5 will be slightly bigger. However, the tip of the end effector is still successfully direct toward the center point of the hemisphere.

Thus, from the Table 4.5, Figure 4.5, Table 4.6 and Figure 4.7, we can concluded that although the tip of the end effector of KUKA youBot did not move in a smooth way like the path of actual coordinate, but the error between the tip the actual coordinate and the measured coordinate is very small, which it behaved very close to what it planned. With this, it can be said that the proposed method is valid, which the tip of the end effector of KUKA youBot is able to face toward the center point of the hemisphere.

4.2.3 Experiment 3: Study on the validity of the proposed method in directing the webcam mounted on the tip of the end effector of KUKA youBot to face toward the center point of the object

When the tip of the KUKA youBot's is able to point toward the center point of the hemisphere, it was then tested by mounting a webcam on the tip of the end effector of KUKA youBot for capturing the video of the object while it was moving from one point to another through the developed path from point 1 to point 5. After the video is captured, the frames of the object from point 1 to point 5 are extracted to measure the position of the reference line, z_F in each of the frame based on the lines on the object as shown in Figure 4.8.

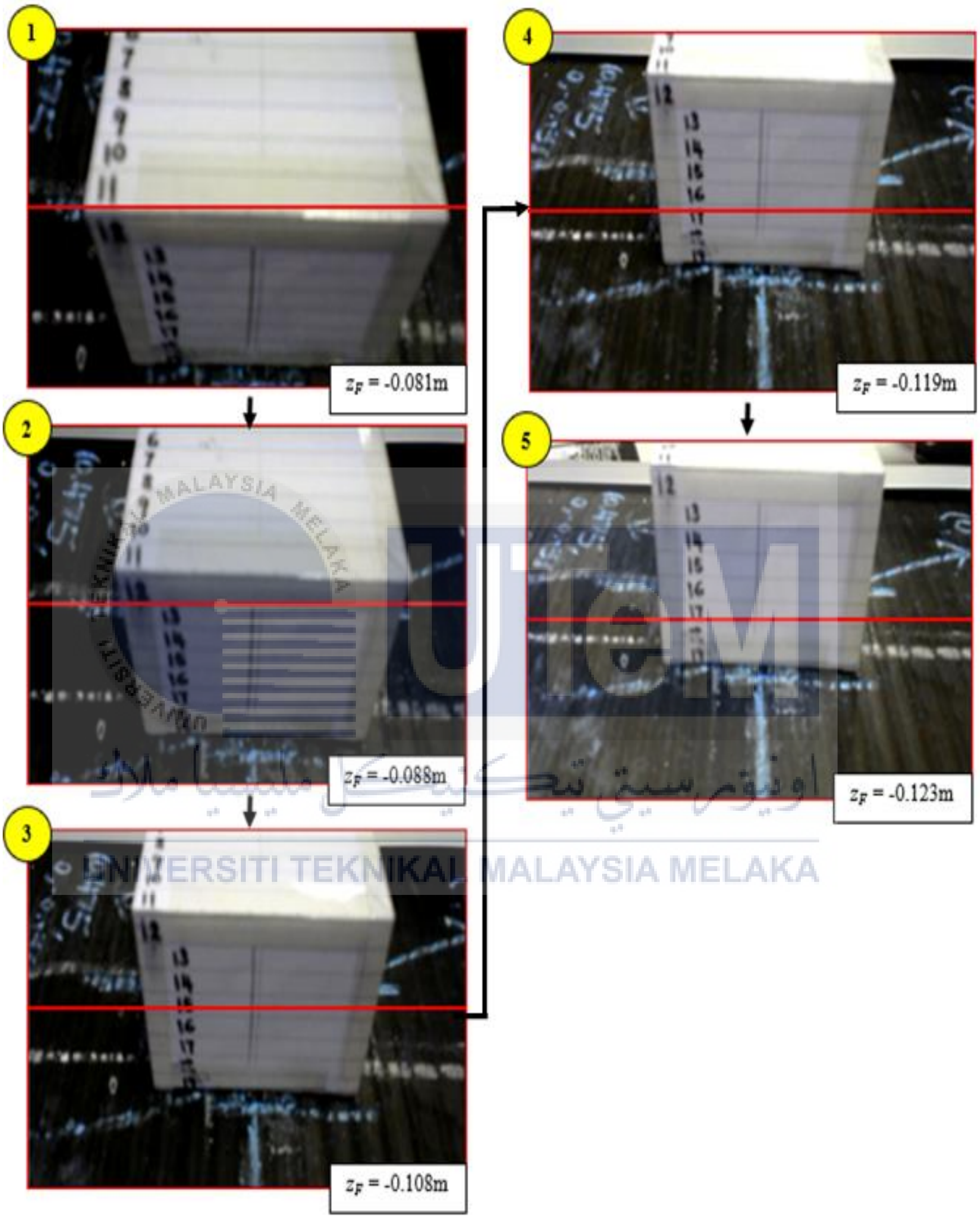

Figure 4.8: Position of the reference line, z_F in each of the frame based on the lines on the object from point 1 to point 5

After the position of the reference line in each of the frame from point 1 to point 5 is measured, it is compared with the actual position of the reference line as shown in Table 4.7 and Figure 4.9.

Table 4.7: The percentage of error between the actual position and measured position of the reference line in each of the frame from point 1 to point 5

Point	Actual position, z_F (m)	Measured position, z_F (m)	Percentage of error (%)
1	-0.081	-0.081	0
2	-0.096	-0.088	8.33
3	-0.107	-0.108	0.93
4	-0.115	-0.119	3.48
5	-0.120	-0.123	2.50
Average percentage of error (%)			3.05

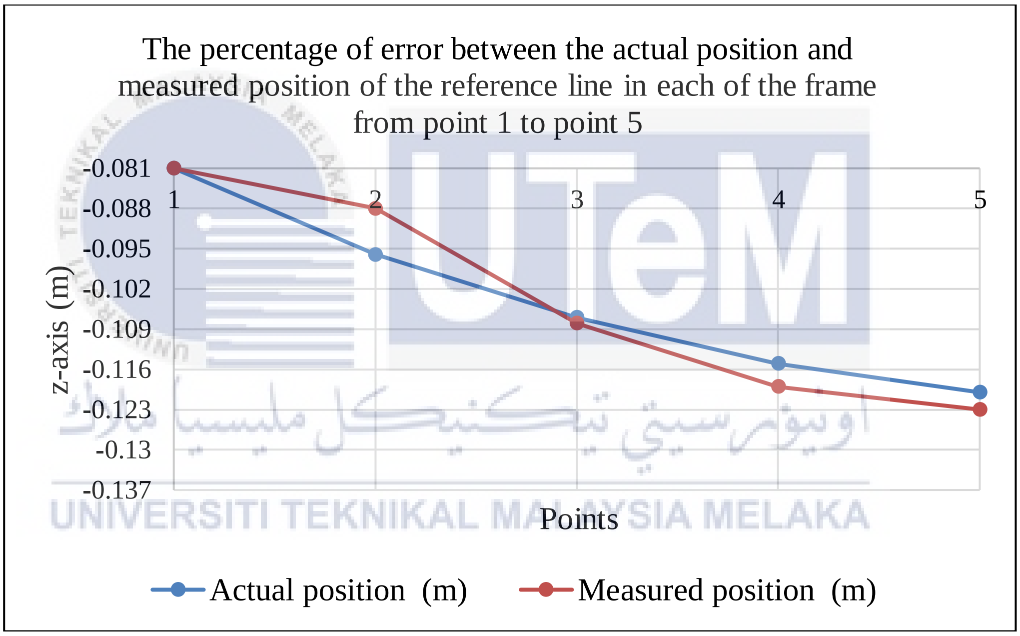

Figure 4.9: Graph of the percentage of error between the actual position and measured position of the reference line in each of the frame from point 1 to point 5

Based on Figure 4.8, through point 1 to point 5, the part which will be captured by the webcam that mounted on the tip of the end effector of KUKA youBot was from column 6 to column 19, which half of the width or top view of the object and the full height or front view of the object are covered. Based on the Table 4.7, the percentage of error between the actual position and measured position of the reference line for the webcam mounted on the tip of the end effector of KUKA youBot to look at, point 1, 3, 4 and 5 is within the range from 0% to 4%, and only point 2 has the percentage of error of 8.33%. However, based on Figure 4.9, the difference between the actual position and measured position for the reference line from point 1 to point 5 is almost the same, which gave the average percentage of error of 3.05% only as shown in Table 4.7. With the small average percentage of error and a quarter part of the object is covered, it can be said that the proposed method is valid as the webcam that mounted on the tip of the end effector of KUKA youBot behaved very close to what it is expected in path planning.

4.3 Summary of the chapter

In short, the objectives for the three of the experiments are successfully achieved. In experiment 1, an imaginary hemisphere surrounding the center point of the hemisphere where the tip of the KUKA youBot’s end effector will be pointing toward is constructed, a path of points is generated on the surface of the imaginary hemisphere, and the position of the tip of the KUKA youBot’s end effector in term of x-coordinate and z-coordinate is able to be analyzed with the average percentage of position error of 1.67%. With this, the proposed method for doing experiment 1 is said to be valid. For experiment 2, the tip of the end effector of KUKA youBot is able to face toward the center point of the imaginary hemisphere, the angle between the joint 3 of the KUKA youBot and the center point of the imaginary hemisphere with the average percentage error of 2.91% is analyzed, and the position of the tip of the end effector of KUKA youBot in term of x-coordinate and z-coordinate with 0.014% for the average percentage of position error is analyzed. From this, it can be see that the proposed method for doing experiment 2 is also valid. As for experiment 3, the reference line of the frame captured by the webcam that mounted on the tip of the end effector of KUKA youBot from one point to another point is analyzed with 3.05% for the average percentage of error. Thus, it can be said that the proposed method for doing experiment 3 is valid too.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, the objectives of this project are successfully achieved. Three experiments are conducted to generate a path of 5 points on the surface of the hemisphere and to validate the proposed path planning method based on the error analysis. The results are presented with the aid of diagrams, tables and graphs.

The first objective to design and develop a path of points on the surface of an object to maximize the point of view of the object is achieved by carrying out experiment 1, 2 and 3. Based on the result in experiment 1, a path of 5 points is generated on the surface of the hemisphere and the tip of the end effector of KUKA youBot able to move to the points generated. Then, based on the result obtained in experiment 2, the tip of the end effector of KUKA youBot able to face toward the center point of the hemisphere from the initial point of point 1 to the final point of point 5. By doing so, the webcam that mounted on the tip of the end effector of the KUKA youBot is also able to face toward the center point of the object, which is situated on the surface of the platform as shown in experiment 3. Thus, the point of view of the object is maximized due to the reason that a quarter part of the object can be captured from different point in different angle.

Next, the second objective of this project, which is to validate the path planning method using error analysis is successfully achieved by carrying out experiment 1, 2 and 3. Based on the result obtained from experiment 1, a path of points is formed on the surface of the hemisphere and the tip of the end effector of KUKA youBot is positioned on the path of points, which the average coordinate difference for x-coordinate and z-coordinate are 0.0087m and 0.0656m respectively and had an average percentage of position error of 1.67% only. As for the result obtained from experiment 2, the tip of the end effector of KUKA youBot able to direct toward the center point of the hemisphere with 2.91% for the average percentage of error for the angle from the center point of hemisphere towards the position of youBot's joint 3, 0.006m and 0.011m for the average coordinate difference for x-coordinate and the z-coordinate of the tip of the end effector of KUKA youBot respectively, and 0.014% for the average percentage of position error for the tip of the end effector of KUKA youBot to be positioned. Meanwhile, based on the result obtained from experiment 3, the webcam that mounted on the tip of the end effector of KUKA youBot able to point toward the center point of the object with the average percentage of error of 3.05% for the position of the reference line, where the webcam will look at, and the coverage of the object from column 6 to column 19 through the developed path from point 1 to point 5. All in all, the proposed path planning method for this project is said to be valid based on the error analysis for the three experiments.

However, there is shortcoming for this proposed method, which this method is only applicable to the system where the joint 3 and the tip of the end effector of KUKA youBot needed to be in parallel in terms of y and z coordinate first. Moreover, the weakness of this youBot is that due to the reason that the workspace of inspection needed to be minimized, the mobile platform of the KUKA youBot is not used because it needs to take a lot of space for its movement from one place to another. With the condition of the arm of the KUKA youBot, which only consists of 5 degree of freedom, the arm of it could only move up and down and cannot move in a horizontal way while pointing toward the center point of the object. Thus, the path of points generated on the surface of the geometry shape could only be in vertical form.

5.2 Future Works

For future improvements, if wants to use KUKA youBot without its mobile platform to maximize the point of view of the object, a turntable can be used for the object to be situated on it. By doing so, all parts of the object can be taken by turning the turntable for 4 times in 90° each. Otherwise, it is recommended to use robot that has more than 5 degree of freedom, so that the arm of the robot can moves in all of the direction, either in horizontal form or vertical form, where the webcam that mounted on the tip of the end effector of the robot manipulator could face toward the center point of the object from every different point.

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APPENDICES

APPENDIX A CODING IN CONSTRUCTING A HEMISPHERE, AND GENERATING POINTS AND A PATH OF POINTS ON THE SURFACE OF THE HEMISPHERE

```
clc;
clear;

[x,y,z] = sphere;      % Makes a 21-by-21 point sphere
x = x(11:end,:);       % Keep top 11 x points
y = y(11:end,:);       % Keep top 11 y points
z = z(11:end,:);       % Keep top 11 z points
radius = 0.287;
c = [0.45 0 -0.137];
hs = surf(radius.*x + c(1),radius.*y,radius.*z,'FaceColor','yellow','FaceAlpha',.3);
axis equal
xlabel('X');ylabel('Y');zlabel('Z');

% set line parameters
np = 5;                          % number of points
LineAzimuth        = 180;    % Azimuth
LineElevationStart = 90;     % Start Elevation
LineElevationStop  = 60;     % Stop Elevation

% generate spherical coordinates
azp = zeros(np,1) + deg2rad(LineAzimuth);
elp = linspace(deg2rad(LineElevationStart),deg2rad(LineElevationStop),np).';
rp  = zeros(np,1) + radius ;

% convert to cartesian
[xp,yp,zp]=sph2cart(azp,elp,rp) ;

hold on
hp = plot3(xp + c(1), yp, zp,'g','LineWidth',2,'Marker','x') ;  % Display the line
plot3(0,0,0,'*');                                               % Display the reference point
plot3(c(1), c(2), c(3),'or');                              % Display center point of hemisphere
```

APPENDIX B INVERSE KINEMATIC CODING

```
#include "ros/ros.h"
#include "boost/units/systems/si.hpp"
#include "boost/units/io.hpp"
#include "brics_actuator/JointPositions.h"
#include <iostream>
#include <stdio.h>
#include <math.h>

using namespace std;

ros::Publisher armPublisher;
ros::Publisher gripperPublisher;



double x_cordinate=0,y_cordinate=0,z_cordinate =0;
int statetest = 1;
// create a brics actuator message with the given joint position values
brics_actuator::JointPositions createArmPositionCommand(std::vector<double>&
newPositions) {
  int numberOfJoints = 5;
  brics_actuator::JointPositions msg;
  if (newPositions.size() < numberOfJoints)
    return msg; // return empty message if not enough values provided

  for (int i = 0; i < numberOfJoints; i++) {

    // Set all values for one joint, i.e. time, name, value and unit
    brics_actuator::JointValue joint;
    joint.timeStamp = ros::Time::now();
    joint.value = newPositions[i];
    joint.unit = boost::units::to_string(boost::units::si::radian);

    // create joint names: "arm_joint_1" to "arm_joint_5" (for 5 DoF)
    std::stringstream jointName;
    jointName << "arm_joint_" << (i + 1);
    joint.joint_uri = jointName.str();

    // add joint to message
    msg.positions.push_back(joint);
  }
  return msg;
}

// create a brics actuator message for the gripper using the same position for both fingers
brics_actuator::JointPositions createGripperPositionCommand(double newPosition) {
```

```
  brics_actuator::JointPositions msg;
  brics_actuator::JointValue joint;
  joint.timeStamp = ros::Time::now();
  joint.unit = boost::units::to_string(boost::units::si::meter); // = "m"
  joint.value = newPosition;
  joint.joint_uri = "gripper_finger_joint_l";
  msg.positions.push_back(joint);
  joint.joint_uri = "gripper_finger_joint_r";
  msg.positions.push_back(joint);

  return msg;
}

  double px=0,pz=0,py=0;
  double theta_base=0, theta_2=0, theta_3=0, theta_4=0;
  double theta_link_1=0 , theta_link_2=0;
  double theta_link_1p=0, theta_link_2p=0;

// move arm once up and down
void moveArm() {
  brics_actuator::JointPositions msg;
  std::vector<double> jointvalues(5);

        double px = x_cordinate;
        double py = -y_cordinate;
        double pz = z_cordinate;

      //////////////////   BASE THETA    /////////////////////////
     py = py;
     double theta_base = atan2 (py,px);

     {
     if (py >=0) {
       theta_base = theta_base + 2.9624;
       //cout << " The value of  " << py <<"\n";
     }
       else {
         theta_base = theta_base - 2.9624 + 5.8201;
         //cout << " Good \n ";
       }
     if (theta_base > 5.8201){
       cout << "NaN";
     }

     if (theta_base < 0){
       cout << "NaN";
     }

     }
```

```
std :: cout << theta_base << std::endl;

////////////////////////////////////////////////////////////

//////////////////    THETAS FOR ARM-LINK 1 2 3 (Inverse Kinematic)  ///////////

double l2 = 0.302 - 0.147;
double l3 = 0.437 - 0.302;
double l4 = 0.655 - 0.437;

double xc = sqrt(px*px +py*py);
double zc = pz;
double phi_c = 0;
double d = sqrt (xc*xc + zc*zc);
//std::cout << " d = " << d << std::endl;

if (d >= 0.500){
  double theta_link_1 = atan2(zc,xc) ;
//break;
}

else if (d == 0.508) {
  double theta_link_1 = atan2(zc,xc) ;
//break;
}

else if (d > 0.508) {
  std::cout << " Co-ordinate Points are out of the work space. \n" ;
//break;1
}

else {
double xw = xc – l4*cos(phi_c);
double zw = zc – l4*sin(phi_c);
double alpha = atan2 (zw,xw);

double cos_beta =  (l2*l2 + l3*l3 -xw*xw -zw*zw)/(2*l2*l3);
double sin_beta = sqrt (abs(1 - (cos_beta*cos_beta)));
double theta_link_2 = 3.1416 - atan2 (sin_beta , cos_beta) ;

double cos_gama = (xw*xw + zw*zw + l2*l2 – l3*l3)/(2*l2*sqrt(xw*xw + zw*zw));
double sin_gama = sqrt (abs (1 - (cos_gama * cos_gama)));
double theta_link_1 = alpha - atan2(sin_gama, cos_gama);

double theta_link_1p = theta_link_1 + 2*atan2 (sin_gama , cos_gama);
double theta_link_2p = - theta_link_2;

double theta_2 = theta_link_1p;
double theta_3 = theta_link_2p;
double theta_4 = (theta_2 + theta_3);
```

```
        //std::cout << " Base Angle " << theta_base << std::endl;
        //std::cout << " Link-1 Angle " << theta_2 << std::endl;
        //std::cout << " Link-2 Angle " << theta_3 << std::endl;
        //std::cout << " Link-3 Angle " << theta_4 << std::endl;

        double j1 = theta_base; //unit in radian
        double j2 = 2.5988 - theta_2;
        double j3 = -2.4352 - theta_3;
        double j4 = 1.7318 + theta_4 + 0.602;

        std::cout << " jointvalue0 " << j1 << std::endl;
        std::cout << " jointvalue1 " << j2<< std::endl;
        std::cout << " jointvalue2 " << j3 << std::endl;
        std::cout << " jointvalue3 " << j4 << std::endl;
        std::cout << " jointvalue4 " << 3.00 << std::endl;

        jointvalues[0] = j1;//unit in radian
        jointvalues[1] = j2;
        jointvalues[2] = j3;
        jointvalues[3] = j4;
        jointvalues[4] = 3.00; //171.887
        msg = createArmPositionCommand(jointvalues);
        armPublisher.publish(msg);
        ros::Duration(1).sleep();
        }
}

void moveGripper() {
  brics_actuator::JointPositions msg;
}

int main(int argc, char **argv) {
  ros::init(argc, argv, "youbot_ros_hello_world");
  ros::NodeHandle n;
  brics_actuator::JointPositions msg;
  std::vector<double> jointvalues(5);

  armPublisher =
n.advertise<brics_actuator::JointPositions>("arm_1/arm_controller/position_command",
1);
  gripperPublisher =
n.advertise<brics_actuator::JointPositions>("arm_1/gripper_controller/position_command"
, 1);
  sleep(1);

  int state;
  state = 1;

        x_cordinate = 0.3065;
        y_cordinate = 0.0;
```

```
      z_cordinate = 0.1115;

moveArm();
ros::Duration(4).sleep();

      std::cout << " x_cordinate :" << x_cordinate << std::endl;
      std::cout << " y_cordinate :" << y_cordinate << std::endl;
      std::cout << " z_cordinate :" << z_cordinate << std::endl;

  msg = createArmPositionCommand(jointvalues);
  armPublisher.publish(msg);

  jointvalues[0] = 0.11;
  jointvalues[1] = 0.11;
  jointvalues[2] = -0.11;
  jointvalues[3] = 0.11;
  jointvalues[4] = 0.111;
  msg = createArmPositionCommand(jointvalues);
  armPublisher.publish(msg);

  return 0;
}
```