การพัฒนาการควบคุมหุ่นยนต์เคลื่อนที่ด้วยระบบวิทัศน์

Set-Point Control of a Mobile Robot with Real-Time Visual Servoing

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รายงานสหกิจศึกษานี้เป็นส่วนหนึ่งในหลักสูตรปริญญาวิศวกรรมศาสตรบัณฑิต

สาขาวิชาวิศวกรรมระบบการผลิต

วิทยาลัยนวัตกรรมการผลิตขั้นสูง

สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง

ปีการศึกษา 2559

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A SPECIAL PROJECT SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
BACHELOR OF ENGINEERING IN MANUFACTURING SYSTEM ENGINEERING
COLLEGE OF ADVANCED MANUFACTURING INNOVATION
KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG
ACADEMIC YEAR 2016

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Year	2016
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College of Advanced Manufacturing Innovation, King Mongkut's Institute of Technology Ladkrabang. Approval a special project submitted in partial fulfillment of the requirements for the degree of bachelor of engineering(Manufacturing System Engineering) Year 2016

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บทคัดย่อ

ในปัจจุบันการควบคุมเซอร์โวของหุ่นยนต์ (Robotic servo control) บนพื้นฐานการตรวจจับวิทัศน์ (Vision sensors) เริ่มเป็นหัวข้อวิจัยที่น่าสนใจมากขึ้น โดยปกติการตรวจจับวิทัศน์มักใช้กับหุ่นยนต์ในสภาพแวดล้อมอุตสาหกรรมที่มีโครงสร้าง โครงการนี้มุ่งเน้นถึงการพัฒนาระบบควบคุมเซอร์โวแบบภาพสำหรับหุ่นยนต์เคลื่อนที่ในห้องปฏิบัติการ ระบบการทำงานหุ่นยนต์เคลื่อนที่จะถูกติดตั้งกล้องบนหุ่นยนต์เพื่อดำเนินการควบคุมจุดตั้งต้นโดยใช้ภาพแบบเรียลไทม์ (real-time images) คุณลักษณะของสีถูกกำหนดเป็นเป้าหมายที่เราต้องการ ความคลาดเคลื่อนในการแปลงข้อมูลถูกกำหนดโดยความแตกต่างระหว่างตำแหน่งที่ต้องการกับตำแหน่งปัจจุบัน รูปแบบการเคลื่อนที่ของหุ่นยนต์และรูปแบบการมองของกล้อง ตลอดจนการเปลี่ยนแปลงความเร็วถูกตรวจสอบ และสุดท้ายการควบคุมเซอร์โวภาพได้ถูกพัฒนาโดยการวิเคราะห์จากคำสั่งความเร็วเพื่อขับเคลื่อนหุ่นยนต์ไปยังเป้าหมาย

<u>คำสำคัญ</u> : *Camera calibration, Mobile robot, Set-point control, Visual servoing*

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ABSTRACT

Nowadays, robotic servo control based on vision sensing has become a popular research topic. Vision sensors are typically employed with robotic manipulators in a structured industrial environment. This project focuses on developing a visual servo control system for a mobile robot in a laboratory environment. The system employs a mobile robot equipped an onboard camera that has been calibrated offline to perform set-point control tasks by using real-time images. Color features are considered as the target to be visually tracked in real time. The encoded error is defined as the difference between the desired and the current feature positions. In the light of the kinematic model of the mobile robot and the perspective projection model of the camera, velocity transformation can be determined. Finally, an image-based visual servo controller is developed to determine velocity command for driving the mobile robot to the target successfully.

Keywords: *Camera calibration, Mobile robot, Set-point control, Visual servoing*

Acknowledgements

Foremost, I would like to express my greatest appreciation to my supervisor, Professor Dr. Wen-Chung Chang, Department of Electrical Engineering, National Taipei University of Technology for his excellent guidance and encouragement throughout the exchange student my research. His dedication and enthusiasm in the field of intelligent robotics and visual servo control applications which can as a source of inspiration for my project in the future as well. I am also thankful for his strong guidance in other aspects of life than research.

I am delighted to express my sincere thanks to my project advisor Dr. Chatrpol Pakasiri in College of Advanced Manufacturing Innovation, King Mongkut's Institute of Technology Ladkrabang, Thailand, for his invaluable comments and suggestions helped me a lot in correcting and improving my project. I would like to thank to my advisor Assistant Professor Dr. Annakapon Saenthon for his assistances, guidance, and encouragement throughout the course of my study.

I would like to express my sincere thanks to all my friends and colleagues in Intelligent Systems Laboratory, Electrical Engineering, National Taipei University of Technology. Especially, Mr. Chia-Hung Wu for his guidance, friendship and encouragement for my project, without his assistance this work could not have been completed on time.

Special acknowledgement, I am grateful to all my professors and my lab members in College of Advanced Manufacturing Innovation, King Mongkut's Institute of Technology Ladkrabang, Thailand, for their enduring help and support who helped me to grow up to the final stage of my education.

I deeply appreciate my parents. Their love and encouragement light up many lonely moments in my life as an undergraduate student away from home and have been the source of courage when I was down.

Sakontanut Srijan

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Chapter 1

Introduction

1.1 Motivation of project

In recent years, the intelligent robot research has a variety of changes. The benefits of development of structured industrial environments to the advancement of autonomous mobile robots operating lead to unstructured and natural environments, such as homes or planet surfaces was developed. These autonomous mobile robots will be abilities in many challenging tasks such as cleaning of hazardous material, surveillance, rescue and reconnaissance in unstructured environments where humans are kept away from. Due to it was predicted that the new version of mobile robots will have widely applications activities where human capabilities are needed, they have attracted the attention of the robotics researchers [1].

Hutchinson and coworkers have presented the basic of robot visual servo control, which involves the control of the orientation and position of a robot via closely integrating the feedback control with the visual information from its CCD cameras [2].

Traditionally, visual servo control has been employed in industrial robotic manipulators so that they can autonomously grasp and move objects of interest in a structured environment with respect to a task trajectory such as grasping vehicle parts moving on a conveyor belt in a production line, for inspection or assembly [3, 4].

Zhang proposes a flexible new technique to easily calibrate a camera. This technique requires a planar checkboard grid to be placed at more than two different orientations in front camera. The developed algorithm used the extracted corner points of the checkboard pattern to compute a projective transformation between the image points of then different images, up to a scale factor. Afterwards, the camera intrinsic and extrinsic parameters are recovered using a closed-form solution, while the third- and fifth- distortion term are recovered within a least-square solution [5].

Compared to traditional visual servo control systems employed in a fixed-base robotic manipulator and visual servo control constituting an autonomous mobile manipulation system has many advantages such as a mobile manipulation system can work in an unstructured environment rather a structured industrial environment. In addition, the arm of manipulator and camera are usually mounted on a mobile base, a mobile manipulation system has better maneuverability and terrain coverage capability than a fixed-base manipulator.

Furthermore, numerous research related to visual servoing and mobile robots has focused on the application of autonomous set-point control or object tracking. For example, Mariottini and Prattichizzo [6] developed an image-based visual servoing approach with central catadioptric cameras for the autonomous of a mobile holonomic robot. They proposed an epipolar geometry based visual servo control approach to drive a mobile robot toward a desired configuration [7]. Amarasinghe *et al.* [8] proposed a vision based hybrid control scheme for autonomous parking of a mobile robot. A discrete event controller was developed to change the direction of travel while an image based visual servoing (IBVS) controller controlled the continuous motion of the robot. A similar work was presented by Nierobisch et al. [9], where a mobile robot with a pan-tilt camera was used to implement visual servo in service robotics. In addition, Chen *et al.* [10] developed a homography-based visual servo tracking control scheme using a wheeled mobile robot. In their project, a prerecorded image sequence of three target points defined the desired trajectory of the robot, and the projective geometric relationships among the images were constructed. Based on the projective geometric relationships, a kinematic controller was developed to implement robust trajectory control. In 2004, Jean and Wu developed a visual servo control technique using shape parameters for object tracking applications. In their paper, an adaptive shape tracking algorithm was developed to dynamically estimate the shape parameters of the object, and a sliding mode controller was proposed to track the object based on the shape information [11].

Based on these motivations, this project is aimed at developing the camera as a sensing element, proposed a visual intelligent space, because the space between the cameras are unknown to each other, through the mobile robot and space in the sensing network to obtain the sensing information calibrate. In this project, we will controlled mobile robot through vision system and camera calibration in order to reach the exploration of the regional environment of the robot to explore the whole region.

1.2 Objective

The main objective of this project can be summarized as follows;

1) To improve the properties of the camera sensing element through the self-calibration technique of the visual servo control system.
2) To applied of algorithm parameters of a library for creating image processing to control mobile robots.
3) To develop an image-based visual servo control system for a mobile robot, which operated in an unstructured environment.

1.3 Project outline

In the proposed approach, this project consists of five chapters;

- Chapter 1 gives general introductions consisting of motivations for this project which have a details interesting work of some researcher. Objective and also project outline are presented.
- Chapter 2 presents an overview of related works which are about basic of image processing, color space, camera calibration, visual servoling, visual servo control and also parameter calibration for mobile robot.
- Chapter 3 explains the algorithms required of a mobile robot controlled to connect with image-based visual servo.
- Chapter 4 presents results and discussion.
- Chapter 5 gives concluding remarks.

Chapter 2

Literature review

This chapter begins with a brief basic of the image processing, color space, camera calibration. A detailed review on visual servoling is also presented. The importance of visual servo control and parameter calibration are discussed in order to thoroughly understand for mobile robot assembly.

2.1 Basic of the image processing

Image processing is a method to convert an image into digital form and perform some operations on it, in order to get an enhanced image or to extract some useful information from it [12]. It is a type of signal dispensation in which input is an image, like video frame or photograph and output may be an image or characteristics associated with that image. Usually the image processing system includes treating images as two dimensional signals while applying already set signal processing methods for them. It is among rapidly growing technologies today, with its applications in various aspects of a business. Image processing forms core research area within engineering and computer science disciplines too.

Image processing basically includes the following three steps.

- Importing the image with optical scanner or by digital photography.
- Analyzing and manipulating the image which includes data compression and image enhancement and spotting patterns that are not to human eyes like satellite photographs.
- Output is the last stage in which result can be altered image or report that is based on image analysis.

2.2 Color space

Color space (also called color model) is to facilitate the specification of colors in some standard, generally accepted way [13]. Color space can be divided into three categories. First, the color space based on HVS (Human Vision System), which consists of RGB, HSI and Munsell color space, etc. Second, the color space based on specific applications, including YUV (be used in the television system), CMY (K) (be used in the printer system) and YIQ color space. The last one is called CIE color space, such as CIE, XYZ, Lab and Luv color space, etc.

1) RGB Color Space

RGB color space is one of the color standards for the industry, and one of the most commonly used color spaces. It is an additive color space in which red, green, and blue lights are added together in various ways to reproduce a broad array of colors [14]. In this color space, all the colors can be expressed by three components (R, G and B), which mean red, green and blue, respectively. When all the components have full intensity, the color is white, and when all the intensity is zero, the color becomes black. Zero intensity in two components and full intensity in the third component give a primary color of the third component. For example, component blue and green have zero intensity, and red component has the full, then the color is red. The RGB color space is represented by a cube in geometric, as shown in Fig. 2.1.

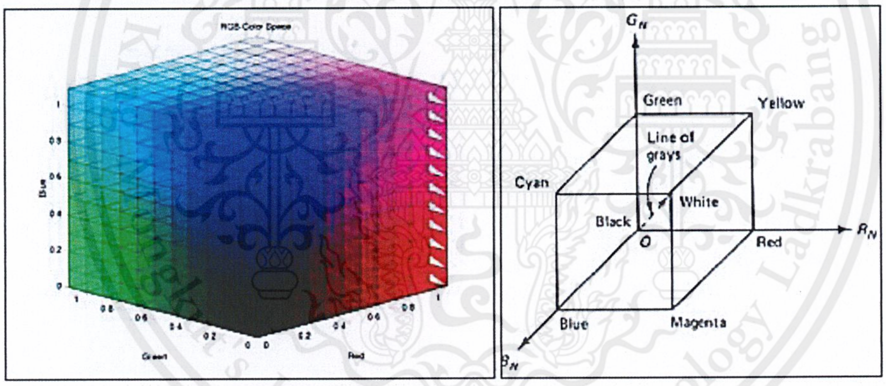

Fig. 2.1 RGB color model [15].

The RGB color space is device-dependent. The relationships between the composition amounts of the three components are unintuitive, and the resulting colors are not specified as absolute.

2) HSV Color Space

HSV color space, which also named the "hexcone model", is proposed based on the visual characteristics of color [16] in 1978. This color space has been widely used in scientific research, such as object tracking [17], face detection [18], and object detection [19]. HSV color model divides color into H (hue), S (saturation) and V (value), which perceives color change independently [20]. It is represented by an inverted cone in geometric, as shown in Fig. 2.2.

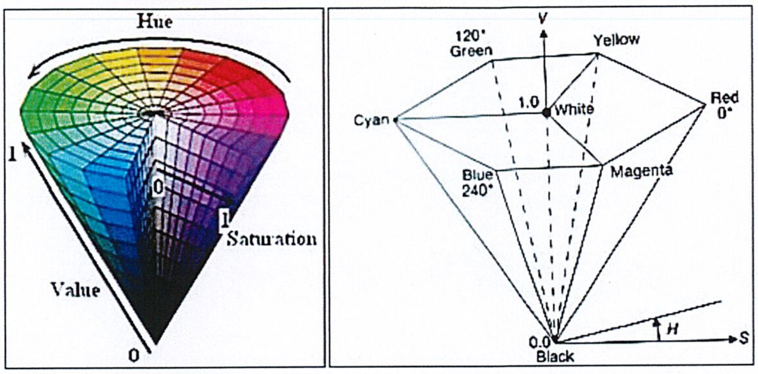

Fig. 2. 2 HSV color model [15].

In the inverted cone, the gray colors comprise the center vertical axis, which ranges from black at value 0 to white at value 1, and the value of the top is 1 while the bottom is 0. The component hue is represented by the angular dimension, which starting from pure red at $^{\circ}0$, across pure yellow at 60°, pure green at 120°, pure blue at 240°, and then turning back to pure red at 360°. The radial dimension of the cone, ranging from 0, the center, to 1, the edge, was labeled as saturation. HSV color space is more intuitive and perceptually relevant than RGB color space [15]. And the components H, S, and V in the HSV color space are more separate than the components R, G, B in RGB color space. A color can be converted from RGB color space to HSV color space with the following expressions:

$$S = \frac{\max(R,G,B) - \min(R,G,B)}{\max(R,G,B)} \tag{2.1}$$

$$H = \begin{cases} 0, & S = 0 \\ 60 \times \dfrac{G-B}{S \times V}, & \max(R,G,B) = R \,\&\, G \geq B \\ 60 \times \dfrac{2+(B-R)}{S \times V}, & \max(R,G,B) = G \\ 60 \times \dfrac{4+(R-B)}{S \times V}, & \max(R,G,B) = B \\ 60 \times \dfrac{6+(G-B)}{S \times V}, & \max(R,G,B) = R \,\&\, G \prec B \end{cases} \tag{2.2}$$

$$V = \max(R,G,B) \tag{2.3}$$

where R, G and B are respectively the normalized values of the RGB color space. The ranges of components H, S and V are [0, 360), (0,1] and [0,1], respectively.

2.3 Camera calibration

Camera calibration is an important step in 3D computer vision in order to pull metric information from 2D images. We can classify those techniques roughly into two categories: photogrammetric calibration and self-calibrate as follows.

- Three-dimensional reference object-based calibration. Camera calibration is performed by observing a calibration object whose geometry in 3D space is known with very good precision. Calibration can be done very efficiently [21]. The calibration object, usually consists of two or three planes orthogonal to each other. Sometimes a plane undergoing a precisely known translation is also used [22]. These approaches require an expensive calibration apparatus, and an elaborate setup.
- Self-calibration techniques in this category do not use any calibration object. Just by moving a camera in a static scene, the rigidity of the scene provides in general two constraints [23], on the cameras' internal parameters from one camera displacement by using image information alone. Therefore, if images are taken by the same camera with fixed internal parameters, correspondences between three images are sufficient to recover both the internal and external parameters which allow us to reconstruct 3D structure up to a similarity [24]. While this approach is very flexible, it is not yet mature [25]. Because there are many parameters to estimate, we cannot always obtain reliable results.

We examine the constraints on the camera's intrinsic parameters provided by observing a single plane. We start with the notation used in this project.

1) Notation

A 2D point is denoted by $\boldsymbol{m}=[u,v]^T$, a 3D point is denoted by $\boldsymbol{M}=[X,Y,Z]^T$. We use $\tilde{x}$ to denote the augmented vector by adding 1 as the last element: $\tilde{\boldsymbol{m}}=[u,v,1]^T$ and $\boldsymbol{M}=[X,Y,Z,1]^T$. A camera is modeled by the usual pinhole: The relationship between a 3D point M and its image projection m is given by

$$s\tilde{\boldsymbol{m}}=\boldsymbol{A}[\boldsymbol{R}\ \ \boldsymbol{t}]\tilde{\boldsymbol{M}},\ \ with\ \boldsymbol{A}=\begin{bmatrix}\alpha & \gamma & u_0\\ 0 & \beta & v_0\\ 0 & 0 & 1\end{bmatrix} \tag{2.4}$$

where s is an arbitrary scale factor, (*R, t*), called the extrinsic parameters are the rotation and translation, which relates to the world coordinate system to the camera coordinate system, and *A* is called the camera intrinsic matrix, with (u_0, v_0) the coordinates of the principal point, α and β the scale factors in the image u and v axes, and γ the parameter describing the skew of the two image axes. We use the abbreviation A^{-T} for $(A^{-1})^T$ or $(A^T)^{-1}$.

2) Homography between the model plane and its image

Without loss of generality, we assume the model plane is on $Z = 0$ of the world coordinate system. Let's denote the *i*th column of the rotation matrix *R* by r_i. From (2.4), we have

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = A\begin{bmatrix} r_1 & r_2 & r_3 & t \end{bmatrix}\begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix} = A\begin{bmatrix} r_1 & r_2 & t \end{bmatrix}\begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \tag{2.5}$$

By abuse of notation, we still use *M* to denote a point on the model plane, but $M = [X, Y]^T$ since *Z* is always equal to zero. In turn, $\tilde{M} = [X, Y, 1]^T$. Therefore, a model point *M* and its image *m* are related by a homograph *H*:

$$s\tilde{m} = H\tilde{M} \quad with\ H = A\begin{bmatrix} r_1 & r_2 & t \end{bmatrix} \tag{2.6}$$

As is clear, the 3 × 3 matrix *H* is defined up to a scale factor.

3) Constraints on the intrinsic parameters

Given an image of the model plane, an homography can be estimated. Let's denote it by $H = [h_1 \quad h_2 \quad h_3]$. From (2.6), we have

$$[h_1 \quad h_2 \quad h_3] = \lambda A[r_1 \quad r_2 \quad t], \tag{2.7}$$

Where λ is an arbitrary scalar. Using the knowledge that r_1 and r_2 are orthonormal, we have

$$h_1^T A^{-T} A^{-1} h_2 = 0 \tag{2.8}$$

$$h_1^T A^{-T} A^{-1} h_1 = h_2^T A^{-T} A^{-1} h_2 \tag{2.9}$$

2.4 Visual servoing

Visual servo control refers to the use of computer vision data to control the motion of a robot. The vision data may be acquired from a camera that is mounted directly on a robot manipulator or on a mobile robot, in which case motion of the robot induces camera motion, or the camera can be fixed in the workspace so that it can observe the robot motion from a stationary configuration. Other configurations can be considered such as, for instance, several cameras mounted on a pan-tilt heads observing the robot motion. The mathematical development of all these cases is similar, and in this tutorial we will focus primarily on the former, so-called eye-in-hand, case.

Visual servo control relies on techniques from image processing, computer vision, and control theory. Since it is not possible to cover all of these in depth in a single article, we will focus here primarily on issues related to control, and to those specific geometric aspects of computer vision that are uniquely relevant to the study of visual servo control. We will not specifically address issues related to feature tracking or three-dimensional (3-D) pose estimation, both of which are topics deserving of their own tutorials.

2.4.1 The basic components of visual servoing

The aim of all vision-based control schemes are to minimize an error $\mathbf{e}(t)$, which is typically defined by

$$e(t) = s(m(t), a) - s^* \tag{2.10}$$

This formulation is quite general, and it encompasses a wide variety of approaches, as we will see below. The parameters in (2.10) are defined as follows. The vector $\boldsymbol{m}(t)$ is a set of image measurements (e.g., the image coordinates of interest points or the image coordinates of the centroid of an object). These image measurements are used to compute a vector of k visual features, $s(\boldsymbol{m}(t),a)$, in which $\mathbf{a}$ is a set of parameters that represent potential additional knowledge about the system (such as coarse camera intrinsic parameters or 3-D models of objects). The vector $\mathbf{s}^*$ contains the desired values of the features.

In Part I of the tutorial (this article), we consider the case of a fixed goal pose and a motionless target, i.e., $\mathbf{s}^*$ is constant, and changes in $\mathbf{s}$ depend only on camera motion. Further, we consider here the case of controlling the motion of a camera with six degrees of freedom (6 DOF); e.g., a camera attached to the end effector of a six degree-of-freedom arm. We will treat more general cases in Part II of the tutorial.

Visual servoing schemes mainly differ in the way that $\mathbf{s}$ is designed. In this article, we will see two very different approaches. First, we describe an image-based visual servo control (IBVS), in which $\mathbf{s}$ consists of a set of features that are immediately available in the image data. Then, we describe a position-based visual servo control (PBVS), in which **s** consists of a set of 3-D parameters, which must be estimated from image measurements.

Once **s** is selected, the design of the control scheme can be quite simple. Perhaps the most straightforward approach is to design a velocity controller. To do this, we require the relationship between the time variation of **s** and the camera velocity. Let the spatial velocity of the camera be denoted by $v_c = (\upsilon_c, \omega_c)$, with vc the instantaneous linear velocity of the origin of the camera frame and ω_c the instantaneous angular velocity of the camera frame.

2.4.2 Classical Image-Based Visual Servo

Traditional image-based control schemes [26, 27] use the image-plane coordinates of a set of points (other choices are possible, but we defer discussion of these for Part II of the tutorial) to define the set **s**. The image measurements **m** is usually the pixel coordinates of the set of image points (but this is not the only possible choice), and the parameters **a** in the definition of $s = s(m,a)$ in (2.10) is nothing but the camera intrinsic parameters to go from image measurements expressed in pixels to the features.

2.5 Visual servo control and parameter calibration for mobile robot

2.5.1 Control strategy

The first step, by observing the error between the current position and the desired position of the image feature point, the mobile robot base attempts to change its position and heading by adjusting the angular velocities of its wheels so as to make the robot base move close to the object and align itself with the object. The second step, the on-board arm approaches and grasps the object using the classical image based eye-to-hand visual servo control scheme, as described in [32]. In this project will be focused on the development of the visual servo control law in the first step.

2.5.2 Kinematic model

In order to derive the control law, four sets of coordinate frames are defined now. They are the robot coordinate frame, the camera coordinate frame, the image plane coordinate frame and the pixel coordinate frame. The relationship between the first two coordinate frames is shown in Fig. 2.3.

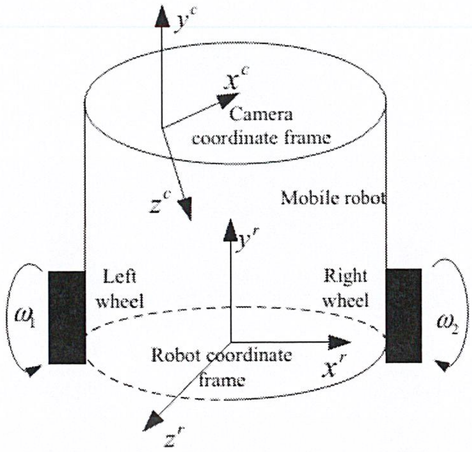

Fig. 2.3 The robot coordinate frame and the camera coordinate frame [33].

In Fig. 2.3, the camera coordinate frame is rigidly attached to the camera while the robot coordinate frame is fixed to the mobile robot. In addition, the coordinate transformation between two frames is given by

$$H_c^r = \begin{bmatrix} R_c^r & d_c^r \\ 0 & 1 \end{bmatrix} \tag{2.11}$$

Here, $\mathbf{R_c^r}$ is the rotational matrix and $\mathbf{d_c^r} = \begin{bmatrix} d_x & d_y & d_z \end{bmatrix}^T$ is the coordinate vector of the origin of the camera coordinate frame with respect to the robot coordinate frame. From (2.11) it is easy to derive the relationship between the camera velocity and the robot velocity [34], as

$$\xi_r^r = \begin{bmatrix} 0 \\ 0 \\ v \\ 0 \\ \omega \\ 0 \end{bmatrix} = \begin{bmatrix} R_c^r & s(d_c^r)R_c^r \\ 0_{3\times 3} & R_c^r \end{bmatrix} \xi_c^c = G\xi_c^c \tag{2.12}$$

Here v and ω are the translational and rotational velocities of the robot with respect to the robot coordinate frame, $\xi_r^r = (v_x \; v_y \; v_z \; w_x \; w_y \; w_z)^T$ is the camera velocity vector with respect to the camera coordinate frame, and $s(d_c^r)$ is the skew symmetric matrix of the vector d_c^r.

Based on the kinematic model of the mobile robot [1], the velocity of the robot can be calculated from the speeds of its wheels as follows:

$$\begin{bmatrix} v \\ w \end{bmatrix} = \begin{bmatrix} D/2 & D/2 \\ D/l & -D/l \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \quad (2.13)$$

Here, Dis the wheel diameter and lies the distance between the two wheels.

2.5.3 Control law

In this project, an image-based visual servo control law is developed. The basic idea is that the controller will continuously adjust the wheel speeds of the mobile robot so that the coordinates (u, v) of the feature point are moved towards the desired position (u_d, v_d) on the image. shows the relationship between the error rate defined on the image plane and the angular velocities of the wheels on the mobile robot. The pixel coordinates can be directly measured from the current image using the available image processing software. Therefore,If the desired angular velocities of the two wheels of the mobile robot can be directly calculated from the image measurements.

Chapter 3

Set-Point Control of Mobile Robot

In experimental chapter, the protocol communication based on a C# program with Emgu library image processing through Microsoft Visual Studio 2010, to find out important characteristics of converting a distorted image were improved. And then , the detected features of find the position to compare with features target. These values were calculated. And to control the direction of movement of the mobile robot. illustrated in Fig. 3.1 and Fig. 3.2.

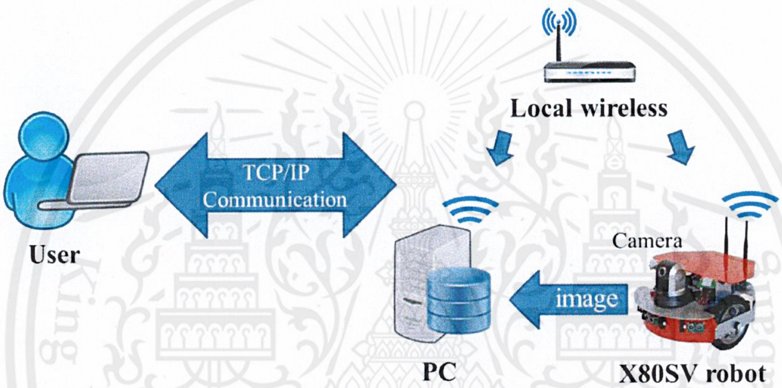

Fig. 3.1 Typical operating scenario

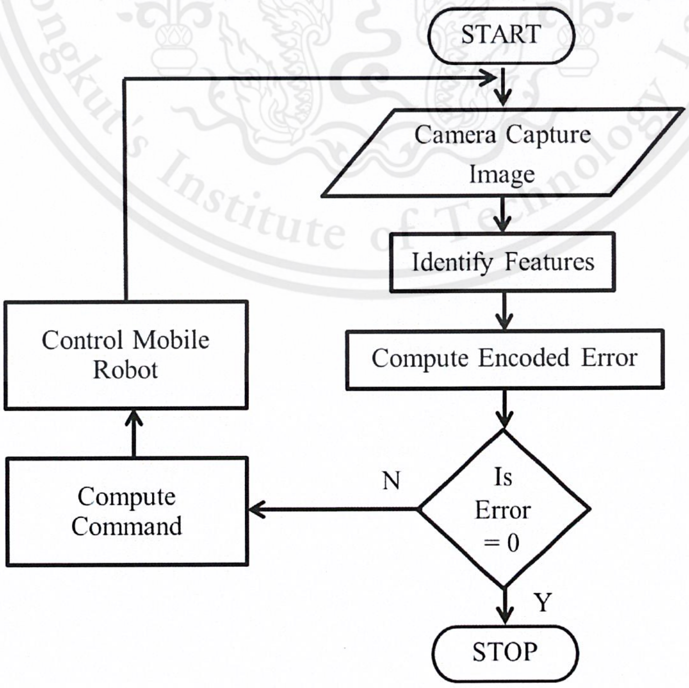

Fig. 3.2 Flow chart of Typical operating scenario

3.1 Operating procedures

3.1.1 Camera calibration and Image processing

In the camera calibration process and image processing, we have studied the intrinsic parameters of the Emgu library to select the appropriate function with the underlying corner geometry of a sequence of images. The camera calibration process. The first step, when the object image was taken with a single camera, the corners of each of the object were calculated the distortion coefficient for the correction the images (also called camera calibration). Then, image processing part is illustrated in Fig. 3.3. the images have been corrected to move into the detected color process for the target object (split color) by using the HSV model and binary classification. Finally, finding conner target position of color space based on HSV model.

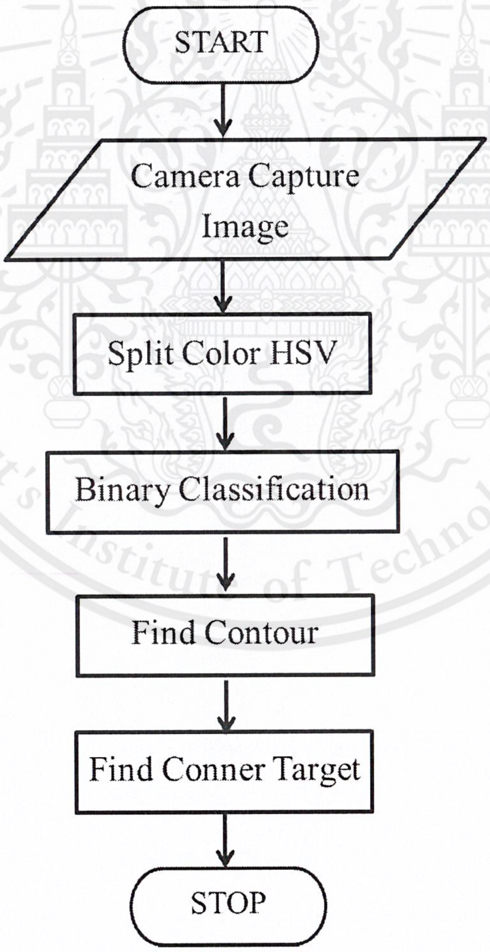

Fig. 3.3 Flow chart of the adaptive camera image processing.

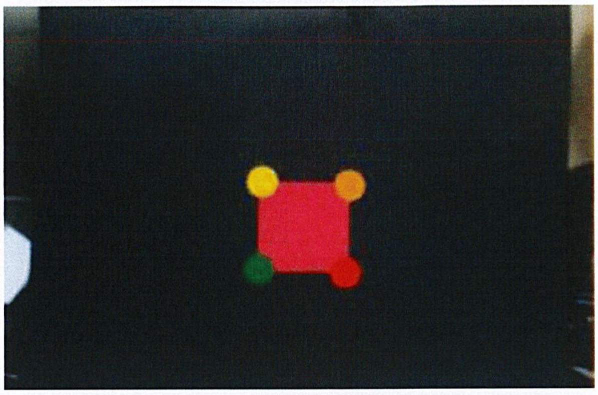

Fig. 3.4 Detection color of target object.

3.1.2 Trajectory planning

Trajectory planning is based on map to create a smooth trajectory. The creation of the trajectory can be seen in Fig 3.5. The control line (red line) is computed to be placed in the middle of the wall.

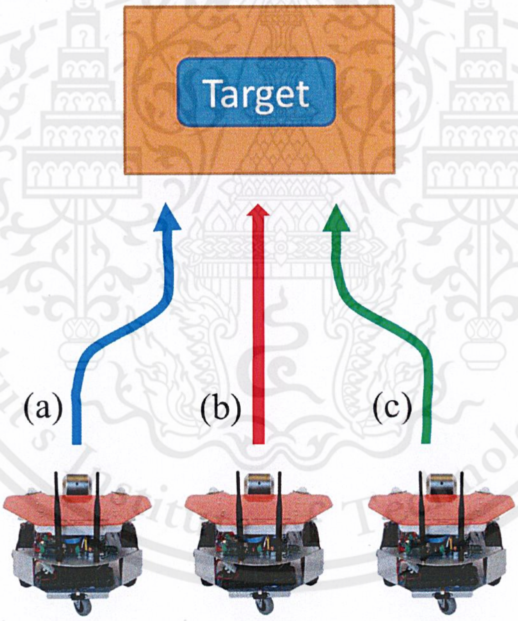

Fig. 3.5 The creation of the trajectory.

3.1.3 Visual servo control

In this section, we have briefly present control mobile robot to move around map control law to help the mobile robot tracking the target is also proposed. The controller diagram for this approach is shown in Fig. 3.6.

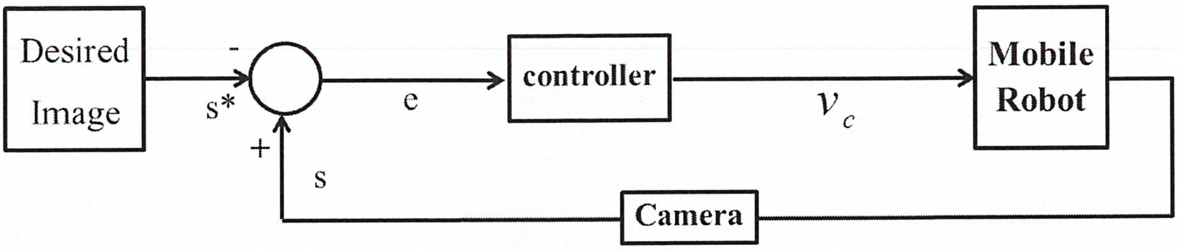

Fig. 3.6 Operation system diagram of the visual servo control.

The error between distance of objects position and target, which can be expanded as written in (3.1)

$$e(t) = s - s^* \tag{3.1}$$

where **s** is the coordinates of the image point from camera frame and **s*** is the coordinates of the image point target. More precisely, for a 3-D point with coordinates $X = (X,Y,Z)$ in the camera frame, which projects in the image as a 2-D point with coordinates $x=(x,y)$, we have:

$$\begin{cases} x = X/Z = (u - c_u)/f_x \\ y = Y/Z = (v - c_v)/f_y, \end{cases} \tag{3.2}$$

where u,v gives the coordinates of the image point expressed in pixel units, and $a = (c_u, c_v, f_x, f_y)$ is the set of camera intrinsic parameters: c_u and c_v are the coordinates of the principal point, and f_x, f_y is the focal length. Traditional image-based control schemes (3.1) use the image-plane coordinates of a set of points

$$\boldsymbol{L_x} = \begin{bmatrix} \frac{-1}{z} & 0 & \frac{x}{z} & xy & -(1+x^2) & y \\ 0 & \frac{-1}{z} & \frac{y}{z} & 1+y^2 & -xy & -x \end{bmatrix} \tag{3.3}$$

For above equation, we can be derived four features , velocity of camera which $\boldsymbol{L_x}$ is derived features and $\boldsymbol{v_c}$ is velocity of camera.

$$\boldsymbol{L_x} = \begin{bmatrix} \boldsymbol{L_{x_1}} \\ \boldsymbol{L_{x_2}} \\ \boldsymbol{L_{x_3}} \\ \boldsymbol{L_{x_4}} \end{bmatrix} \tag{3.4}$$

$$\boldsymbol{v_c} = -\lambda \boldsymbol{L_e^+ e} \tag{3.5}$$

where $L_e^+ \in R^{6\times k}$ is chosen as the Moore-Penrose pseudo-inverse of L_e, that is

$$L_e^+ = \left(L_e^T L_e\right)^{-1} L_e^T \tag{3.6}$$

This is the basic design implemented by most visual servo controllers.

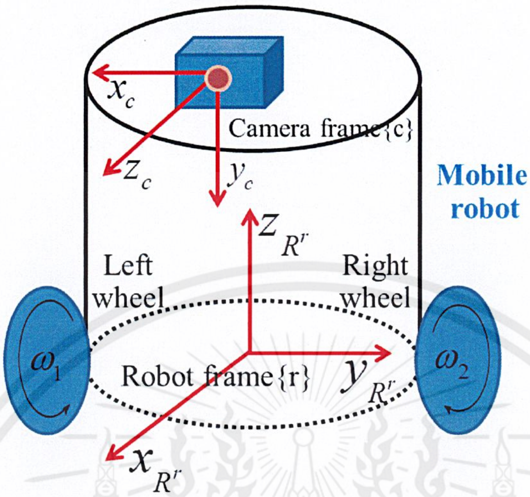

Fig. 3.7 The relations of robot frame and the camera frame.

$$\xi_r^r = \begin{bmatrix} v \\ 0 \\ 0 \\ 0 \\ 0 \\ \omega \end{bmatrix} = \begin{bmatrix} R_c^r & s(d_c^r)R_c^r \\ 0_{3\times 3} & R_c^r \end{bmatrix} \xi_c^c = G\xi_c^c \tag{3.7}$$

Here v and ω are the translational and rotational velocities of the robot with respect to the robot coordinate frame, $\xi_r^r = (v_x\ v_y\ v_z\ \omega_x\ \omega_y\ \omega_z)^T$ is the camera velocity vector with respect to the camera coordinate frame, and $s(d_c^r)$ is the skew symmetric matrix of the vector d_c^r.

In the present project, the depth information Z^C in the interaction matrix (3.3) can be estimated using the on-board distance finder of the mobile robot in a real time manner.

In this project, an image-based visual servo control law is developed. The basic idea is that the controller will continuously adjust the wheel speeds of the mobile robot so that the coordinates (u, v) of the feature point are moved towards the desired position (u_d, v_d) on the image. In particular, the error vector of the image feature point is defined as(3.1)

$$\boldsymbol{e} = \boldsymbol{L}\xi_c^c = \boldsymbol{L}\boldsymbol{G}^{-1}\xi_r^r = \boldsymbol{N}\begin{bmatrix} u \\ v \end{bmatrix} \tag{3.8}$$

Here, N is a 8 × 2 matrix which is constituted by the third and the fifth columns of LG^{-1}. we get

$$\boldsymbol{e} = \boldsymbol{N}\begin{bmatrix} d/2 & d/2 \\ d/l & -d/l \end{bmatrix}\begin{bmatrix} \omega_L \\ \omega_R \end{bmatrix} \tag{3.9}$$

Equation (3.9) shows the relationship between the error rate defined on the image plane and the angular velocities of the wheels on the mobile robot. Based on (3.9), a proportional controller based on the *Lyapunov method* is designed as

$$\begin{bmatrix} w_L \\ w_R \end{bmatrix} = \begin{bmatrix} -d/2 & d/2 \\ d/l & d/l \end{bmatrix}^{-1} (-\lambda \boldsymbol{N}^{-1}\boldsymbol{e}) \tag{3.10}$$

Here, λ is the scalar proportional gain, with $\lambda > 0$.

In (3.10), the pixel coordinates u and v can be directly measured from the current image using the available image processing software. Therefore, according to (3.10), the desired angular velocities of the two wheels of the mobile robot can be directly calculated from the image measurements.

3.2 Operation principle

3.2.1 Protocol connection

The X80SV is a wireless robot, which connected to a local computer *via* a WiFi 802.11b/g network. The local computer running the X80SV control program could connect to this network *via* either:

- Network cable – to connect the host PC to one of the LAN ports on the back of the router, or
- Wireless – to connect the local PC to the wireless router, configure the Local PC's wireless settings using the default wireless configuration settings found in the network connection session.

Fig. 3.1 shows the typical operation scenario for this project. The manufacturer website can be found at [35] for more details on this device.

3.2.2 Mobile robot details

The robot stands on two wheels with 18 cm diameter, each of them connected to a 12V DC-motor that can be controlled independently. The built-in commands allow three types of control for the two DC motors: open loop Pulse-Width Modulation (PWM), closed loop position control and closed loop velocity control, as shown in Fig. 3.8

Fig. 3.8 X80SV mobile robot

The regulators for the wheels are of proportional-integral-derivative type (PID), the values for the PID parameters such as the k_P, k_I, k_D values, can be set by the use of built-in commands. We have used for the PID the values that are also used in the demo application given by the producer.

3.2.3 Software development

In this project, we used Microsoft Visual Studio 2010 *via* library (.dll) such as Emgu version 2.4, Matrix, and Demo X80SV library image processing.

Chapter 4

Experimental Results and Analysis

4.1 Target of feature

After sensing In Fig 4.1. Describes the direction of movement of the mobile robot, which are classified in three different directions of motion.

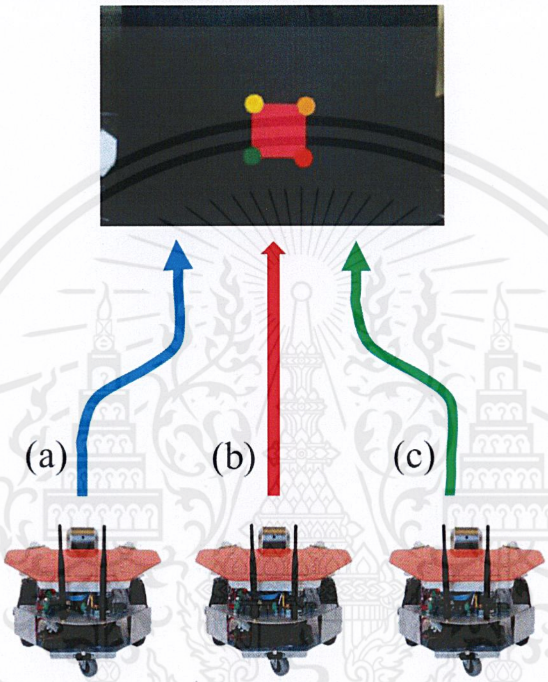

Fig. 4.1 Direction mobile robot three way

4.2 In the first case

In this case, the detected error of four points (objects) on the right side of the mobile robot The mobile robot is a curve to the right. Figure 4.2 shows that the error occurred decreased as shown in Figure 4.3. The position of the starting point to the target position in Figure 4.4, and a presentation on the subject of speed, direction, as shown in Figure 4.5.

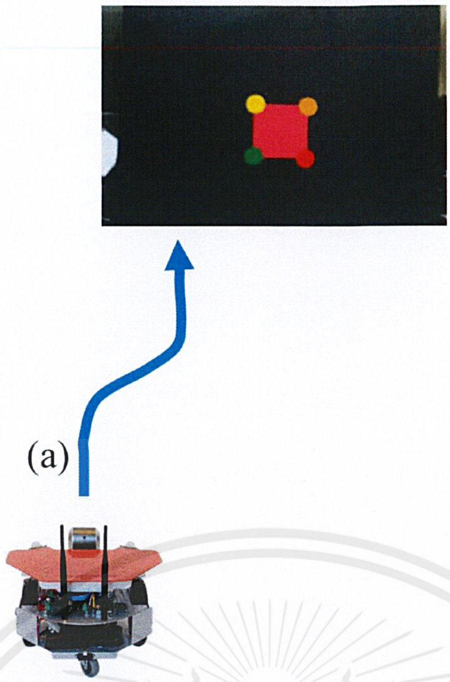

Fig. 4.2 Mobile robot on left side

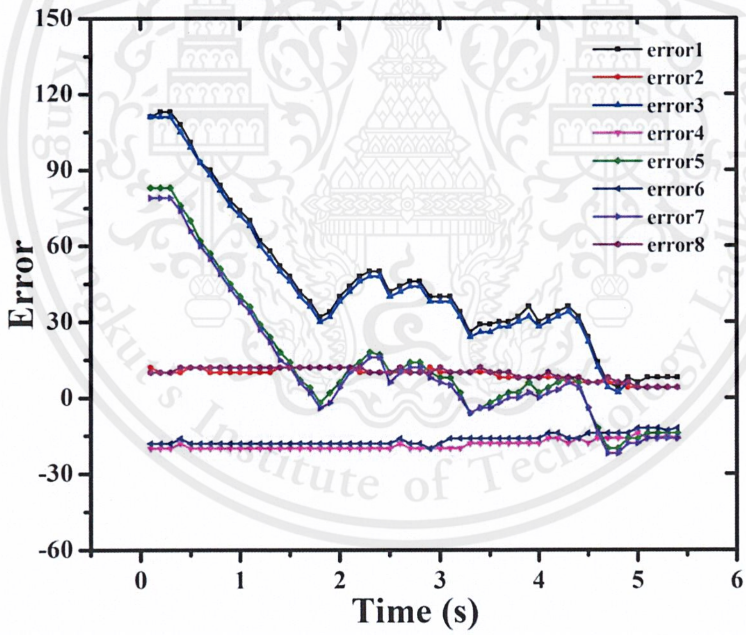

Fig. 4.3 The error of all the feature point on left side

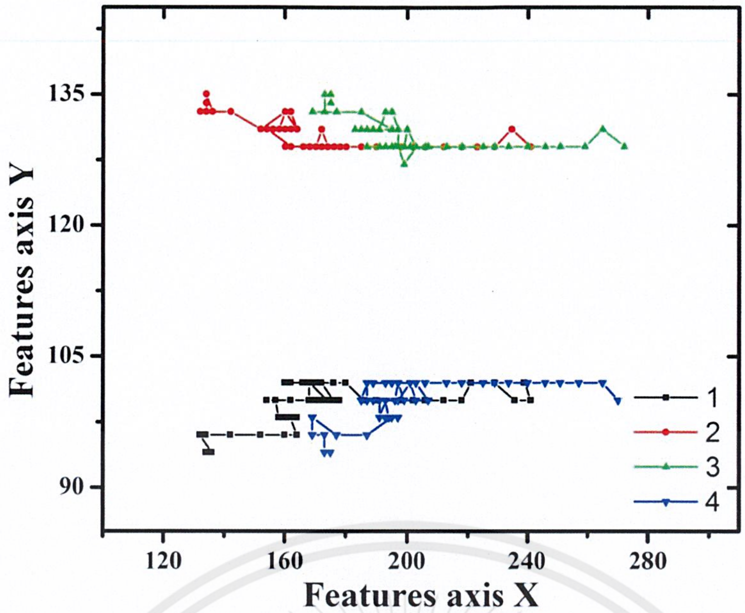

Fig. 4.4 Image point trajectory of the center for the square (left line movement)

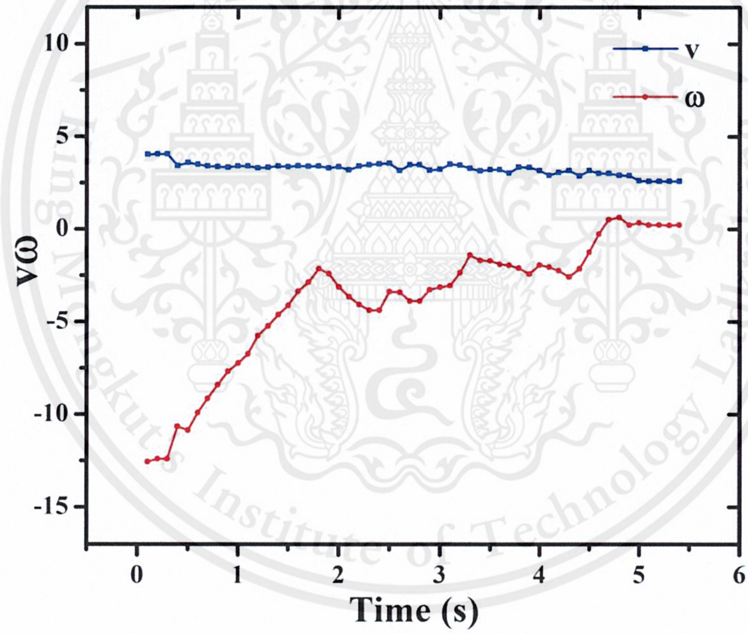

Fig. 4.5 Velocity and rotation of mobile robot at left line.

4.3 In the second case

In this case, the detected error of four points (objects) on the front of the mobile robot The robot moves in a straight line. As shown in Fig. 4.6. It can be seen that the error occurred decreased as shown in Fig. 4.7. The position of the starting point to the target position in Fig. 4.8, and a presentation on the subject of speed, direction, as shown in Fig. 4.9.

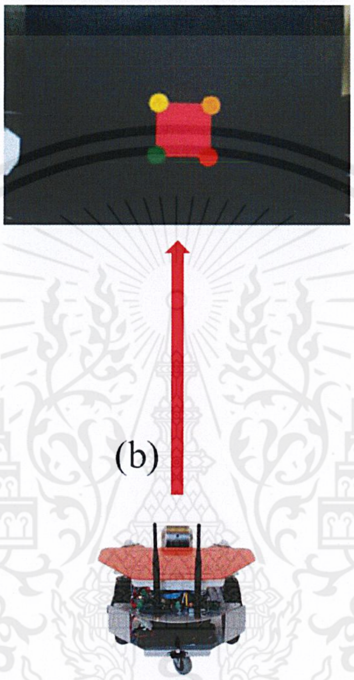

Fig. 4.6 Mobile robot on straight line

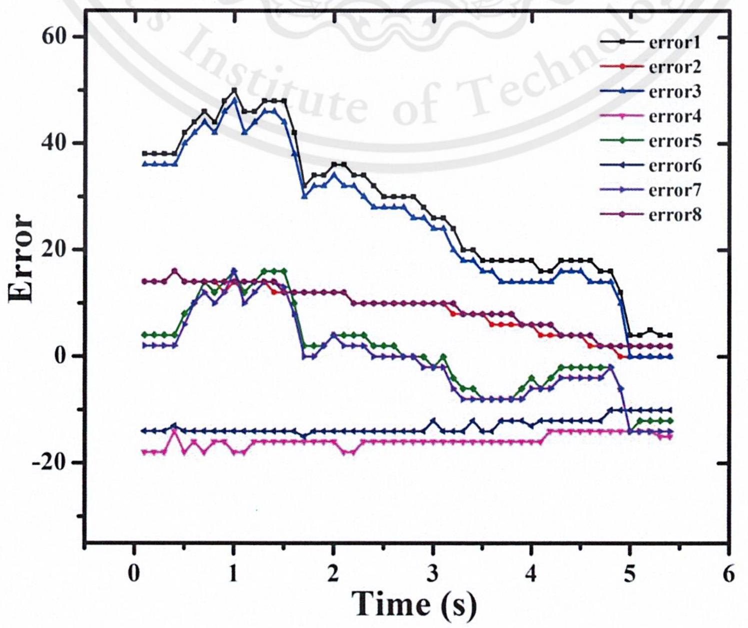

Fig. 4.7 The error of all the feature point on straight side

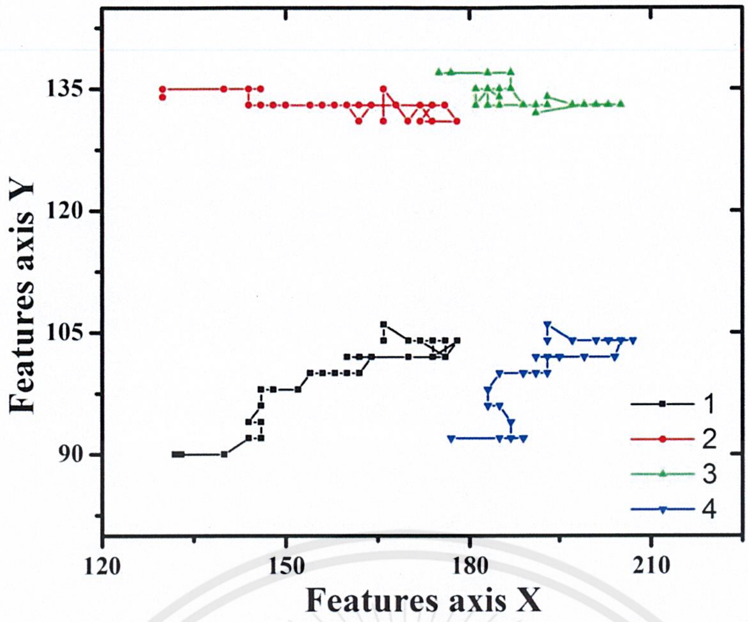

Fig. 4.8 Image point trajectory of the center for the square (straight line movement)

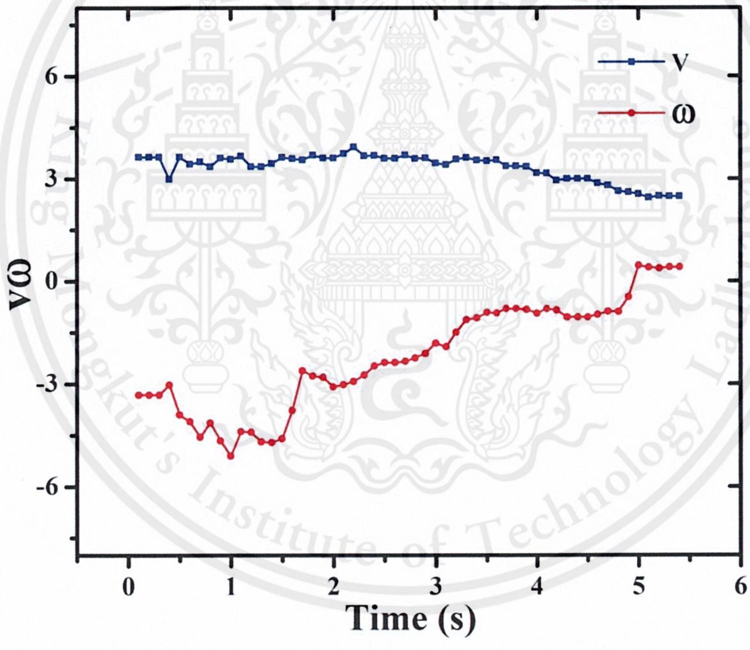

Fig. 4.9 Velocity and rotation of mobile robot at straight line.

4.4 In the third case

In this case, the detected error of four points (objects) on the left side of the mobile robot The mobile robot is a curve to the left. Figure 4.10 shows that the error occurred decreased as shown in Figure 4.11. The position of the starting point to the target position in Figure 4.12, and a presentation on the subject of speed, direction, as shown in Figure 4.13.

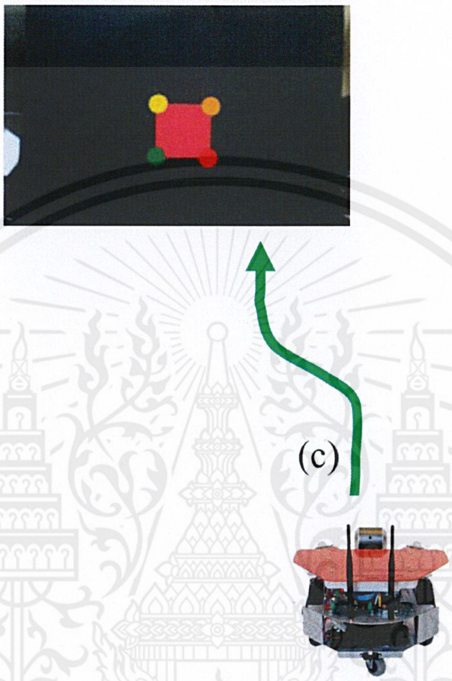

Fig. 4.10 Mobile robot on right side

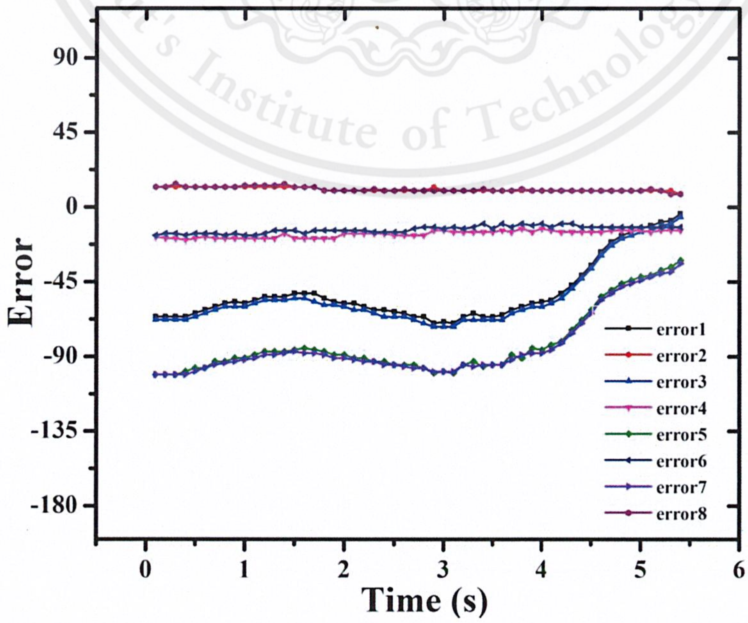

Fig. 4.11 The error of all the feature point on right side

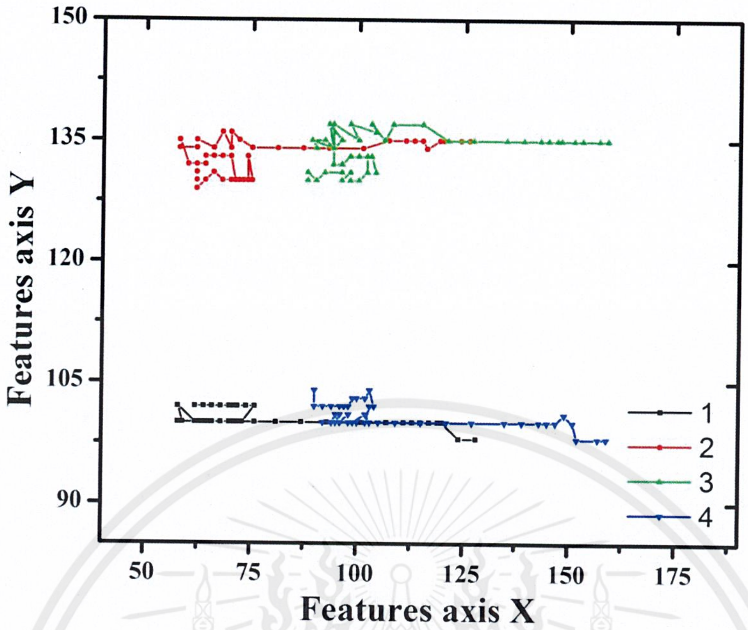

Fig. 4.12 Image point trajectory of the center for the square (right line movement)

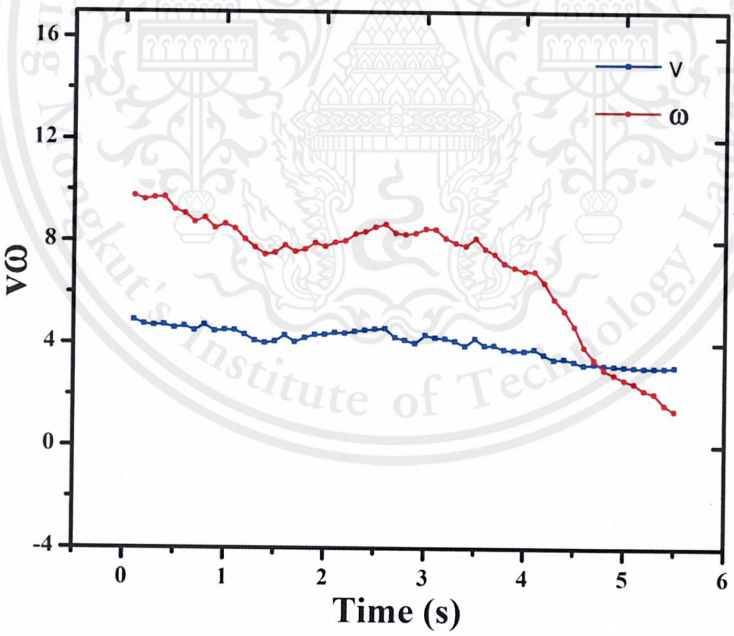

Fig. 4.13 Velocity and rotation of mobile robot at right line.

4.5 Results of the work

Error of feature

The error of all the four feature points are shown in Fig. 4.1, Fig. 4.7 and Fig. 4.11. The error of straight line of mobile robot reveals that decreased trend in every seconds, this feature point is small error.

Whereas the curve line of right side and left side shown the same trend, but their position and direction of rotation is not a straight line, resulting in an adjustment to new rotary to obtain the target as desired.

The results showed that all the three feature point follows their desired images with small errors. The images used in the image processing tends to be closer to zero, indicates that the mobile robot moving target.

Feature at four point

All three direction graphs noticed that the velocity of camera indicated the direction of motion between the camera and the target objects, which expresses the coordinates and velocity of visual servo.

Chapter 5

Conclusion and Future extension

Nowadays, the visual servo control based on the image processing has become a popular research topic in robotics. Usually, it is applied to fixed-base robotic manipulators working in a structured industrial environment. This project focuses on developing an image-based visual servo control system for a mobile robot, which operates in an unstructured environment. Firstly, the issue of camera calibration of the visual servo control system and control objective are improved. Secondly, it is used to detect objects. Using image processing find position. And the design features target. Finally, the value of image processing to calculate the movement of the mobile robot to the target.

5.1 Conclusion

This paper studied the visual servo control for mobile robots. Using the kinematic models of a mobile and a camera, a proportional control law was derived based on the Lyapunov stability method. The derived controller, which is a form of image-based visual servo controller. The results showed that all three feature the following images to their errors are small images used in image processing are likely to be close to zero, indicating that mobile robots moving target. Which error of values potential of the servo was used for more may be corrosion.

5.2 Future extensions

The future will have to improve on the speed of imaging. The cameras used are slow. Might be to choose a camera with a higher quality. The use of light to assist in the process. For better results and can be applied in the future.

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