2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Attitude Control of Quadrotor with On-Board Visual Feature Projection System

Jaehong Lee[1] , Changmin Lee[2], and DaeEun Kim[3]

Abstract— **Recently many researches have been studied to run autonomous flying vehicles. Especially, quadrotor VTOL (Vertical Take-Off and Landing) has been a challenging subject. To stabilize the quadrotor system, many control algorithms and sensor systems have been developed. Most of them are based on the sensors like accelerometer, gyroscope, or IMU (Inertial Measurement Unit) to measure the attitude of quadrotor. Instead of using these conventional sensors, we apply one vision sensor to stabilize the attitude of a quadrotor system. To achieve this, four laser diodes are evenly distributed in the bottom plane of quadrotor, and then they point downwards. The positions of projected laser markers depend on the attitude and height of the quadrotor. We develop a control algorithm to stabilize the attitude as well as to control the height of a quadrotor. We show that the visual tracking of the laser markers is sufficient to estimate the state of the quadrotor attitude and control the attitude into a desired state.**

Fig. 1. Quadrotor platform

I. INTRODUCTION

A quadrotor, which uses four rotors to obtain thrust, is one of famous VTOL (Vertical Take-Off and Landing) or UAV(Unmanned Aerial Vehicle) systems. The concept of quadrotor first appeared in 1920s. This system is suitable for both civil and military missions such as fire detection of forest, traffic surveillance, and enemy surveillance. In addition, it can be utilized in hazardous environments via remote sensing. For example, Barthlmai et al. [1] tried gas measurement in a volcanic crater.

Controlling quadrotor is simply accomplished by varying the speed of four rotors. As it is relatively easy to control the robot and the system has good stability, the quadrotor system has gained great popularity recently and many researches have been done by using this system. This system is so stable that even a swarm control of quadrotors have been developed in many studies. They can cooperate to transport some objects [2] or build cubic structures [3].

To stabilize a quadrotor system, many sophisticated control algorithms were suggested. Some researchers tested LQ (Linear Quadratic) servo control [4]. The PID control method for this system seems one of popular approaches [5] [6]. There were also a fuzzy control method to make self-tuning PID controller [7] [8] and Hoffmann et al. [9] used Kalman filter for attitude estimation and control of the quadrotor system.

[1]Jaehong Lee is with Electrical and Electronic Engineering, Yonsei University, Seoul, Korea leejaehong@yonsei.ac.kr

[2]Changmin Lee is with Electrical and Electronic Engineering, Yonsei University, Seoul, Korea lcmin@yonsei.ac.kr

[3]DaeEun Kim is with Electrical and Electronic Engineering, Yonsei University, Seoul, Korea daeeun@yonsei.ac.kr

Likewise, various control methods were applied to the quadrotor system. Also, many kinds of sensor systems have been tested in the quadrotor. Grzonka et al. [10] used a laser ranger finder for mapping and path planning, and Rondon et al. [11] performed position and speed regulation of a quadrotor by using vision sensor. Bouabdallah and Siegwart [12] utilized IMU, vision sensor, and ultrasonic sensor. They used sonar sensors to avoid obstacles and measure the altitude of a quadrotor.

Vision sensor is widely used as it gives much information about environments. In [11], downward vision sensor is attached to the quadrotor so that the quadrotor can follow the virtual road zone that can be distinguished by color segmentation processes. Ahrens et al. tested drift-free hover and obstacle avoidance flight with image sensor [13]. Tournier et al. used more pattern targets on the ground with vision sensor to control the quadrotor system [14] and Lange et al. utilized landing pad that consists of rings as visual feature for autonomous landing [15]. Optical flow, which is a biologically inspired algorithm from insects like honey bees [16] and flies, is also implemented to perform localization [17], hovering and vertical landing [18].

However, among these various sensor systems, attitude measurement sensors are essential to control the quadrotor system. Accelerometers and gyroscopes are typical sensors to estimate the attitude. The disadvantages of sensors can be eliminated by adapting filter algorithms. Kalman filter is one of them. Foxlin used accelerometers to compensate for gyroscope drift with Kalman fiter and this method is a common approach for IMU (Inertial measurement Unit) [19].

IMU based control is simple and it ensures stability. However, in this system, additional sensors are required to

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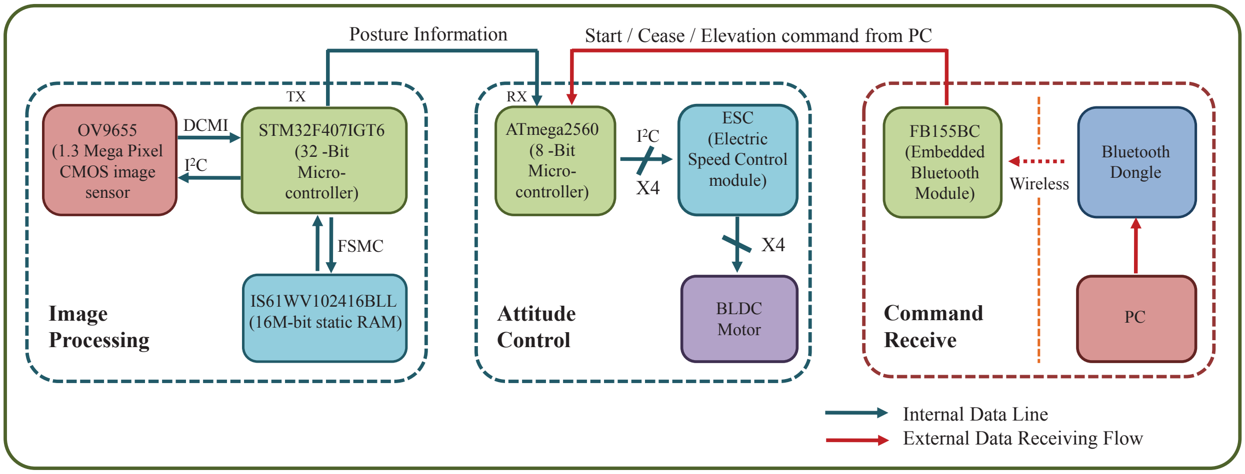


Fig. 2. Hardware block diagram

sense the height of the quadrotor. In this paper, we focus on the vision sensor to control the attitude of a quadrotor. We only use one vision sensor with laser markers. In the previous studies [11], [14], [15], markers are basically located on the ground. However, if the quadrotor misses the target feature, it cannot be controlled based on the visual image and it should try to find and move to the ground marker. To eliminate this situation, we mounted four laser diodes and a downward vision sensor on the quadrotor hardware. Four laser diodes are evenly distributed. As marker generators, laser diodes are located on the quadrotor hardware, and vision sensors can detect those projected laser markers on the ground all the time without missing them when the quadrotor is in stable status. Tilting motion of a quadrotor gives distorted laser marker patterns and those patterns can be analyzed to estimate the attitude of the quadrotor. Also, the altitude can be calculated by using laser markers, without adding other sensor. We will demonstrate the detailed method and results with a real robot.

II. System Overview

A. Hardware Description

Fig. 1 shows the quadrotor hardware that we used. This is propelled by four brushless DC motors (BLDC motor) and those speeds are controlled by ESC (Electric Speed Control) module. These ESC modules use I2C interfaces to communicate and those are connected to ATmega2560 microcontroller. ATmega2560 controls the attitude of quadrotor by adjusting the speed of the rotors with control algorithm. For the image processing, OV9655 image sensor and STM32F407IGT6 micro controller are used. As its internal memory is not enough to handle the image data, external high speed SRAM are used as a buffer. 5-DOF IMU and embedded Bluetooth module are used to monitor the attitude of the hardware on PC. However the IMU is not used for attitude control and used for recording the position information. The whole systems are powered by 11.1V 3cell

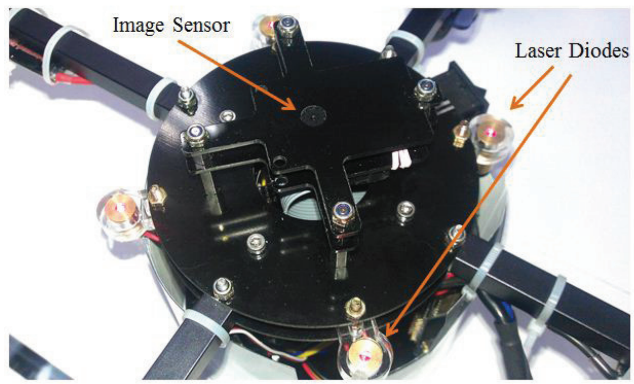


Fig. 3. Image sensor with laser diodes

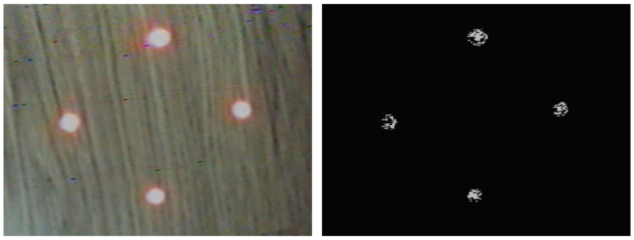
Li-po battery with voltage regulators. These are depicted in Fig. 2.

B. Laser Marker

Fig. 3 is the picture of an image sensor and laser diodes. Four laser diodes as marker generator are mounted on the main frame of hardware. Two pair of laser diodes are arranged orthogonally to each other. Each position of the laser diodes can be adjusted. When the quadrotor is flying, laser lights will be projected on the ground. Those projected laser markers can be detected by a vision sensor.

C. Communications

Using Bluetooth, four kinds of commands can be transferred to the quadrotor from a host PC. These commands are start-up, ceasing, throttle, and height command. Initially, start-up signal should be transferred to the quadrotor to turn on the ESCs. After ESCs are turned on, the quadrotor starts to control its attitude based on the height command. It will try to sustain a given altitude. Users can give throttle data to control the altitude of the quadrotor manually. For the safety



(a) (b)

Fig. 4. Laser marker on the ground (a) original image from the vision sensor (b) converted image with HSV format

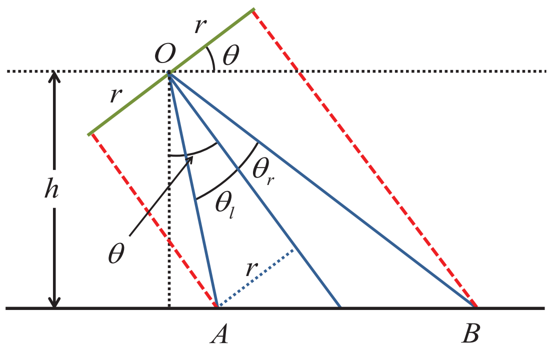


Fig. 5. Roll axis tilting

reason, the cease command is added and when it receives the cease command, it will immediately turn off the ESCs.

The exact roll and pitch angles of a quadrotor are consistently measured by the 5-DOF IMU. The attitude information is transmitted to PC vial Bluetooth communication to monitor the status of a quadrotor.

III. Method

A. Laser Marker Extracting

The system can capture 320 by 240 pixel image for image processing. From the vision sensor, the RGB image is obtained and we convert this image to the HSV format. Thresholds for HSV values are set empirically and used to extract the feature of the laser markers. Pixels that have laser marker information, i.e, the pixels which have higher HSV values than the threshold values are clustered. Then four clusters which represent each laser markers can be obtained. The coordinates of laser markers are determined by taking the mean values of the X and Y locations of pixels for each cluster. Then the locations of four laser markers can be obtained on the 320 by 240 plane coordinate and those locations will vary depending on the attitude or height of the quadrotor. Converted image and its original image are shown in Fig. 4.

B. Calculating the Geometrical Attitude

Fig. 5 shows when the quadrotor is tilted. Let O be the center of the quadrotor and it is tilted by the angle θ. Then the two laser markers will appear with angle θ_l and θ_r from the

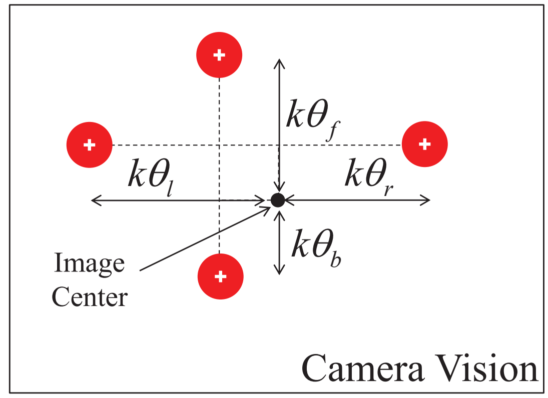


Fig. 6. Example of vision image when the quadrotor is tilted for both roll and pitch axes

image. Ignoring the effects of focal length and FOV (Field Of View) of the vision sensor, the following relationships can be easily derived:

$$\overline{OA} = \frac{h}{\cos(\theta - \theta_l)} \tag{1}$$

$$\overline{OA} = \frac{r}{\sin\theta_l} \tag{2}$$

By subtracting Eq. (2) from Eq. (1), θ can be calculated as follows:

$$\theta = \theta_l + \cos^{-1}\left(\frac{h\sin\theta_l}{r}\right) \tag{3}$$

Also, θ_r can be utilized to calculate the roll angle θ:

$$\overline{OB} = \frac{h}{\cos(\theta + \theta_r)} = \frac{r}{\sin\theta_r} \tag{4}$$

In the same manner, the following can be obtained:

$$\theta = -\theta_r + \cos^{-1}\left(\frac{h\sin\theta_r}{r}\right) \tag{5}$$

If the quadrotor is tilted along both roll and pitch axes, the obtained image will be like an image shown in Fig. 6. If the rotation of two axes is considered, θ_f and θ_b can be added and k is constant. Similarly, the pitch angle can be calculated. However, to calculate the geometrical attitude with these equations, the altitude information h is required. Altitude information cannot be easily obtained without using barometers, ultrasonic sensors, or GPS. So, we consider another way to estimate it.

C. Obtaining Attitude Information

We assumed a quadrotor hovering or flying above the flat surface, without any obstacles on the ground. The laser markers form a quadrangle on the ground and the vision sensor can recognize those markers. The attitude information, as well as roll and pitch angles can be obtained by calculating

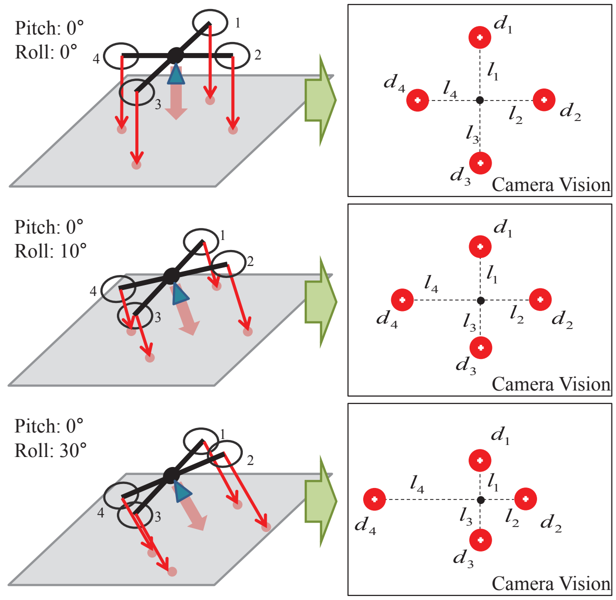


Fig. 7. Vision image with varied attitude in the same altitude

the geometry of the four markers if we know the altitude of the quadrotor. Instead of solving the geometry, a voting mechanism is used as our quadrotor has no sensors for altitude measurement. After getting coordinate information of the laser markers projected on the ground, each marker is labeled as d_1 to d_4 in a clockwise direction. A pair of markers in the orthogonal direction are positioned in the same axis, and we can draw two connected lines to find the intersection point. The coordinate of the intersection point can be easily calculated. The distances from the intersection point to each marker are labeled as l_1 to l_4 as depicted in Fig. 7. When the quadrotor is tilted on the roll axis, the lengths l_1 and l_3 will be reduced as the projection distance is increased. However, the ratio, l_1/l_3 will be maintained as 1 in this case. l_2 and l_4 will be moved to the left side as shown in Fig. 7. Inclination to the pitch axis will affect two distances l_1 and l_3. The lengths, l_1 to l_4 will change depending on the attitude of the quadrotor, that is, the pitch and roll angles. A voting mechanism is implemented by using the lengths l_1 to l_4 with the following equations:

$$le^{i\rho} = \sum_{k=1}^{m} l_k e^{i\rho_k} = x + yi \tag{6}$$

$$x = \sum_{k=1}^{m} l_k \cos(\rho_k),\ y = \sum_{k=1}^{m} l_k \sin(\rho_k), \tag{7}$$

$$\rho = \arctan(y/x),\ \ l = \sqrt{x^2 + y^2} \tag{8}$$

where l_k is the length of intersection point to the k-th laser marker, m is the number of the laser markers, and ρ_k is the angular position for the k-th laser marker direction. Angular position can be represented as follows:

$$\rho_k = r \cdot (k - 1) \tag{9}$$

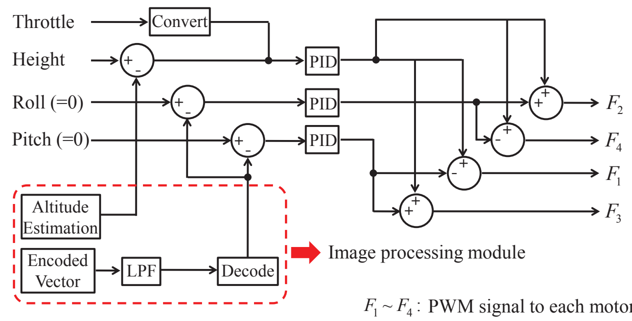


Fig. 8. Block diagram of attitude controller

where r represents the angular resolution. In this case, four laser markers are used and the resolution will be $360°/4 = 90°$, where ρ_1 is equals to $0°$ and ρ_3 will be $180°$.

As k is 4 for our system, estimated vector through Eq. (6)-(9) can be simplified by the following equation:

$$x = l_1 - l_3, \quad y = l_2 - l_4 \tag{10}$$

Though the actual roll and pitch angles cannot be calculated with this method, the calculated vector contains sufficient attitude information. The information is forwarded into a low-pass filter to reduce noise and the filtered attitude information is transferred to our attitude controller.

D. Attitude Control

With given encoded vector information, the attitude controller gives weighted motor commands to the ESCs. The basic goal of attitude controller is to make the ratio of l_1/l_3 and l_2/l_4 to be 1. The second basic goal is to make the lengths l_1, l_2, l_3 and l_4 equal. Then the zero vector will be obtained which indicate equilibrium status of roll and pitch axes at Eq. (8). By using calculated ρ from Eq. (8), the controller can recognize which direction is elevated. Then it reduces the output for the motors located in an elevated side, while increasing the output at the opposite side of ρ direction. To determine these weighted motor commands, PID control method is applied and control block diagram is shown in Fig. 8. With this method, we can avoid intense computation and determine the motor output sufficiently.

E. Altitude Estimation

To estimate the altitude of UAVs, GPS or ultrasonic sensor can be used [12]. Instead of using those sensors, we encode the information with the visual information. We consider the area of quadrangle which is formed by connecting those four laser marker vertices. The area varies depending on the quadrotor attitude. However, when the quadrotor is flying with stable attitude, we can utilize the area information to estimate the altitude of quadrotor. Basically, the area will decrease proportionally to the square of the height as the height increases. The example is shown in Fig. 9. As the altitude is changed from $h1$ to $h2$, the area of quadrangles will be changed from A_{h1} to A_{h2}.

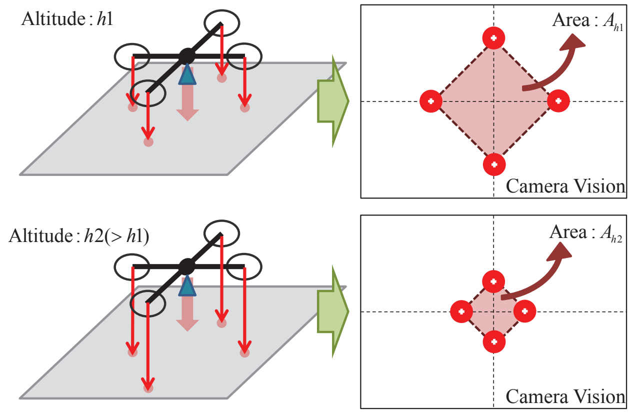


Fig. 9. Vision image with varied altitude

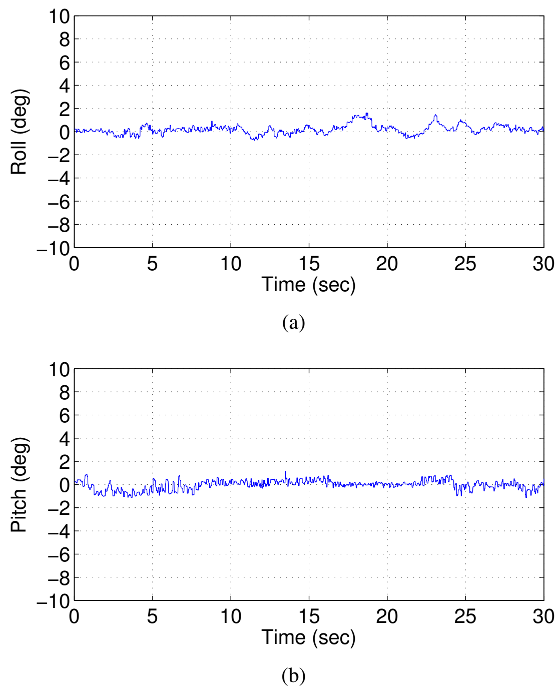


Fig. 10. Attitude data during stationary hovering (a) Roll angle (b) Pitch angle

To obtain the accurate altitude information, other information like focal length and FOV (Field Of View) of the image sensor should be considered [20]. Instead of considering this kind of information, a look-up table can be used.

IV. Demonstration

A. Attitude Stabilization

The attitude controller stabilizes the roll and pitch angles with a PID controller. Attitude of a quadrotor is measured with 5-DOF IMU. As orientation sensors like magnetic compass are not mounted on the quadrotor, the yaw angle is not measured. Fig. 10 shows the behavior of the roll and pitch axes of the hardware while it is performing autonomous flight. Fig. 11 shows the quadrotor hovering.

Fig. 11. Quadrotor in hover

B. Altitude Estimation

The altitude estimation experiment was performed by varying the heights from 20cm to 180cm. The area of projected quadrangle is calculated using the cross product of vectors instead of using trigonometric function to minimize the computation. Fig. 12 shows the relationship between the altitude and the area. Altitude data are collected with 5cm steps. As expected, the area of the quadrangle is decreased as the altitude is increased. Theoretically, altitude estimation graph shows a quadratic form. However, due to the focal length and FOV of the vision camera, the result does not follow a complete quadratic form. Based on the cubic spline data interpolation, a look-up table can be applied for height estimation.

V. Discussion

To minimize the image processing delay, a small size of image (320 by 240) information is used. However, to realize more sophisticated control, larger images with a processor that has better computational performance can be used. With better visual resolution, the altitude estimation error can be reduced. In addition, instead of using four laser markers, a larger number of laser markers can be applied. To extract the laser markers, we used the HSV method for colored images. However, it is easily affected by the light environment. Other robust feature extracting algorithm such as mean shift can be implemented to handle this problem. In our demonstration, we do not consider the height estimation when the quadrotor is not in a stable attitude. However,

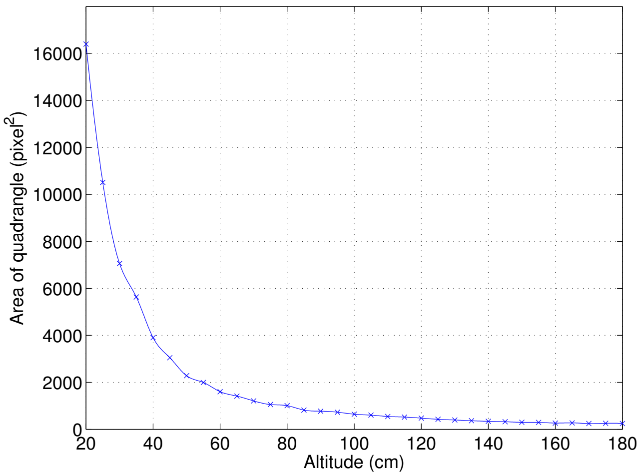


Fig. 12. Relationship between the altitude and the area of the quadrangle that is formed by the laser markers

the height can be calculated regardless of the attitude if the relationship between the inclinations and the area of the projected quadrangle is defined. Warping of the yaw axis direction due to the anti-torques from the rotors is not handled in our work. However, without adding other sensors, the optical flow algorithm can be adapted to the images to compensate for the yaw axis. Instead of using laser markers and vision sensor, four ultrasonic sensors could be mounted. In this case, measured distance from each sensor can give attitude information of the quadrotor.

VI. Conclusions

In this paper, we showed that stabilization of a quadrotor system can be achieved by using a small number of sensors, laser diodes and a visual camera. As the laser light has straightness, projected laser markers on the ground contains attitude information of the quadrotor. With this reason, laser diodes are used to generate active target markers. There are many studies that use a vision sensor and passive ground target markers to control the quadrotor. Similar to the studies of [14] and [15], markers are positioned on the ground in our system. The vision sensor of our system hardly miss the markers as the marker sources are mounted on the quadrotor when it is operated in indoor. The markers form a special pattern depending on the attitude, roll and pitch angles as well as the height of a quadrotor. Possibly inverse kinematics over angles for roll and pitch could be investigated for the attitude control, but we achieve a simple attitude control in real time.

Compared to the IMU based system, this method has many limitations. It cannot be used on non-flat ground and with strong sunlight environment. However, the interesting point is that only one vision sensor can be used to estimate attitude and altitude, and the method also has a possibility to achieve yaw control. For surveillance purpose, vision sensor is essential. If we utilize the vision information with the suggested method, it might be used as a back up system for standard stabilization approaches such as IMU based control.

Acknowledgment

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MEST) (No. 2012R1A2A4A01005677).

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