Experimental study on four rotor helicopter 10 m-range distance and position measurement method by using two searchlights for autonomous control and the evaluation

Hideki Toda

Department of Electric and Electronic Engineering, University of Toyama, Japan, Gofuku 3190

Abstract—*This paper reports experimental result of a distance and position measurement method for autonomous movement control of four-rotor helicopters (drones) that uses two spotlights and comparing with a red marker using case, discuss the results of autonomous flight test evaluations. To conduct autonomous drone flights exceeding 10 m under unstable GPS signal situations, such as under bridges or inside tunnels during periodic maintenance inspections, correct self-positioning measurements are indispensable. This study proposes a simple method whereby autonomous drone movement control can be performed over distances exceeding 10 m by using two high-power 100 V alternating current spotlights set on the ground as infrared (IR) light sources. The spotlights are directed at the investigation target, such as the cracked area of a bridge, and the intense light of the two spotlights provides reference points that enable the drone to determine its correct position. In autonomous flight-testing in an enclosed corridor, our method provides capable of determining the drone's position at distances up to 15 m with a standard deviation of 0.31 m. Our proposed method would be effective in situations where no skilled drone control operator is available and for flights requiring visual cue confirmations under adverse outdoor conditions.*

Keywords—Infrared spotlights, Four-rotor helicopter, Long distance measurements, Bridge/tunnel investigations.

I. INTRODUCTION

In this paper,a distance and position measurement method for autonomous movement control of four-rotor helicopters (drones) that uses two spotlights and discuss the results of a related autonomous flight test evaluation. To achieve drone flights in excess of 10 m under unstable global positioning system (GPS) signal situations, such as under bridges or inside tunnels and buildings during periodic maintenance inspections, an easy and precise self-positioning measurement method is indispensable for stable control [1,2]. This is because, even if a drone is human controlled, it is difficult for an operator to manipulate the device in flight at distances in excess of 10 m using visual cues alone [3-12]. In those situations, other supporting mechanisms are necessary for drone control and position measurements [3,4,13-26]. The aim of this study is to propose a simple method whereby autonomous drone movement control can be performed over distances exceeding 10 m by using two high-power 100 V alternating current (AC) spotlights set on the ground as infrared (IR) light sources (Fig. 1) and it is comparing with the general method of using a red colored marker board attached to the drone. In our method, the spotlights are directed at the investigation target position, such as the cracked area on the side of a bridge [2].

Since drone helicopters are seldom equipped with internal autonomous position controls, ground-based positioning systems based on IR light sources, three-dimensional (3D) cameras, or GPS sensors are needed control their positions during flight [10,11,22-28]. In the case of methods using IR or 3D cameras, the position measurement precision can be on the order of 1 mm, but these methods are normally restricted to indoor situations at distances less than 10 m [5,13]. On the other hand, if a drone is being controlled in an outdoor situation, GPS signals can be used as long as there are limited numbers of obstacles in the skyward and movement directions. However, when using a drone for periodic inspection under bridges or inside tunnels, neither of the abovementioned two approaches can be adopted because distances tend to be excessive and GPS signal reception under bridges or within tunnels is often unstable [2]. If a drone position is detected based on visual cues, cameras can be used to measure its position. This is known as visual-servo control [26-29]. However, in situations where there are numerous obstacles in the camera image, it is difficult for the controlling operator to ascertain a drone's position based on camera imagery alone, especially at distances in excess of 10 m from the starting point.

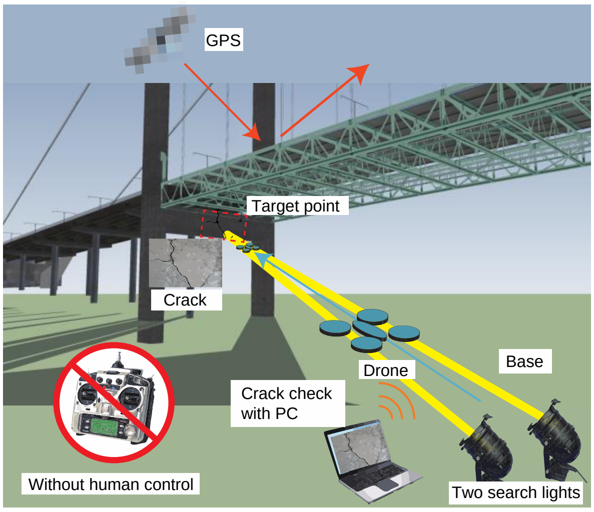

FIGURE 1: Proposed distance measurement method for autonomous drone flights at distances in excess of 10 m using two high-power 100 V AC spotlights set on the ground

II. METHODS

A basic overview of the proposed method is shown in Fig.2. Two high-power spotlights (Stage Evolution, PAR56SBG equipped with 16 cm diameter Sylvania PAR56 300W halogen lamps, Sound House Corp.) were used to provide ground-based IR light sources. A 320 × 240 pixel, 30 frame per second (fps) quarter video graphics array (QVGA) camera (Trek 2000, Ai-ball) mounted at the front of the drone was aligned in the direction of the two spotlights and controlled by using the positions of those spotlights on the camera image based on the center of gravity (CoG) of two points using simple proportional control. An IR filter (IR76, Fuji Filter, Fujifilm Corp.) was mounted on the front of the camera lens. The Ai-ball wireless camera was selected due to the excessively large time delay of the drone's internal camera imagery and control command transmissions (>around 100 msec). Since the Ai-ball camera was positioned at the front of the drone, the drone moved in the backward direction when approaching to the target position. Drone control was provided by the ARDroneForP5 library (Y. Shigeo) control suite [30].

To estimate the drone position, the spotlight positions were extracted from the camera image. An example image is shown in the middle of the right side of Fig. 2(c). The green extracted image areas are approximately 10 pixels wide when the drone is 15 m away from the lights.

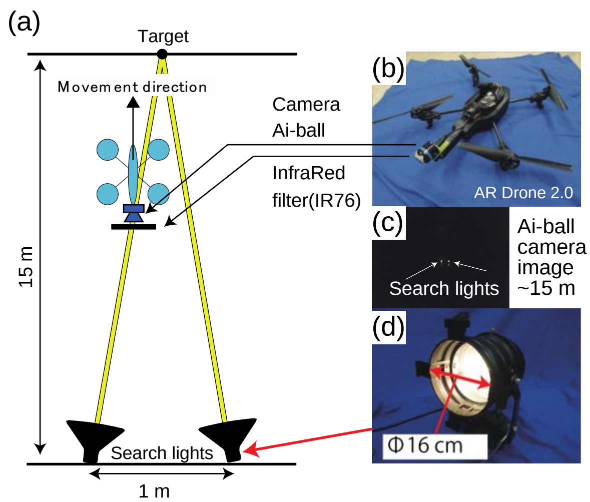

FIGURE 2: Basic concept of drone 10+ m range position measurement method. (a) Two spotlights (PAR56BSG, Stage Evolution) were used to provide IR light sources for in-flight drone position measurements. (b) Using drone system (A.R.Drone 2.0). (c) Search light positions in the camera image. (d) Using spot light.

III. EXPERIMENT

3.1 Experiment 1: Condition of red fluorescent marker attached to drone facing rearward

Drone position estimations have been commonly performed via techniques such as IR light reflection marker(s) or red marker(s) attached to the drone [3,4,10,13]. Marker positions are captured by camera(s) installed in the environment. The conventional method used in Experiment 1 confirmed the stability of drone's position measurement by means of a single red fluorescent marker attached to the rearward facing side (5065 fluorescent sheet red, Myst Corp.) (Fig. 3) of the drone during a 15 m autonomous movement control experiment in an enclosed university corridor. The drone position was determined by using the red fluorescent marker attached to the rearward facing side of the drone via the view from a fixed camera located on the ground. The flight time was 50 sec. Various sized red fluorescent markers (100 × 100, 150 × 150, 200 × 200 mm) and 320 × 240 pixels, 30 fps fixed camera (C270, Logicool Corp.) were used for the position measurements in this experiment.

For the control method, when the CoG of the red fluorescent target marker (Fig. 4a) is (G_x, G_y) and the area is A in the fixed camera image, the drone's movement roll and pitch speed commands $V^r_{command}$, $V^p_{command}$ were described as,

$$V^r_{command} = \gamma_r(160 - G_x)$$
$$V^p_{command} = \gamma_p \quad (1)$$

Where the meaning of γ_r, γ_p are constants.Simple proportional feedback was used in the experiment. γ_p used the drone on a 10% constant forward movement setting. The γ_r feedback parameters were determined by 30 sec continuously measured flight control experiments (N>100 times) in order to minimize the standard deviation (SD) of G_x. The sign for parameter γ_p was changed when the drone approached the target distance of approximately 15 m (23 sec of flight time). The distance z from the camera was calculated from the conversion function = $g(A) \sim \frac{\alpha}{\sqrt{A}}$, which had been previously measured by using a geometric layout of the camera and Area A. The control command sending speed was approximately 100 msec since it is the limit of communication speed (command sending) of the drone used in our experiment. The rotational (yaw) direction was slightly changed (< 1°) after 50 sec of controlled flight and the height of the above from the ground was maintaining at approximately 0.8 m via the drone control mechanism (G_y was not used in the experiment). This type of visual servo system has been adopted in many remote-control aircraft control procedures, including four-rotor drones [13-15].

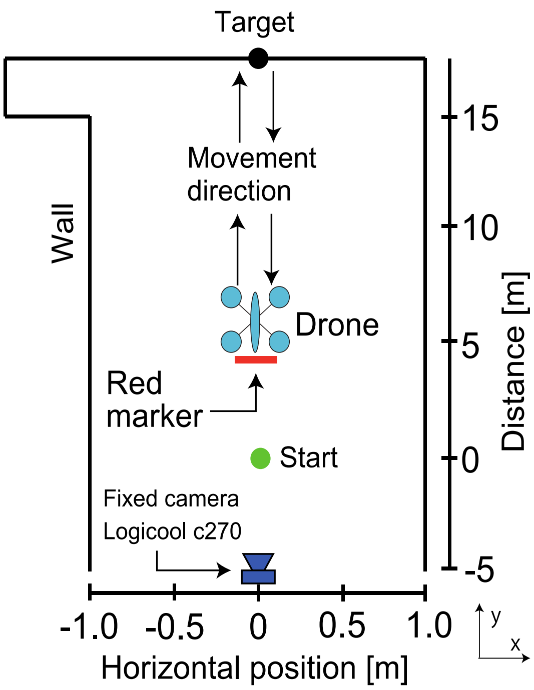

FIGURE 3: Experiment 1 setup for 15 m autonomous movement control experiment in an enclosed corridor (conventional method) using various sized red fluorescent markers (100×100, 150×150, 200×200 mm) attached to the drone facing rearward.

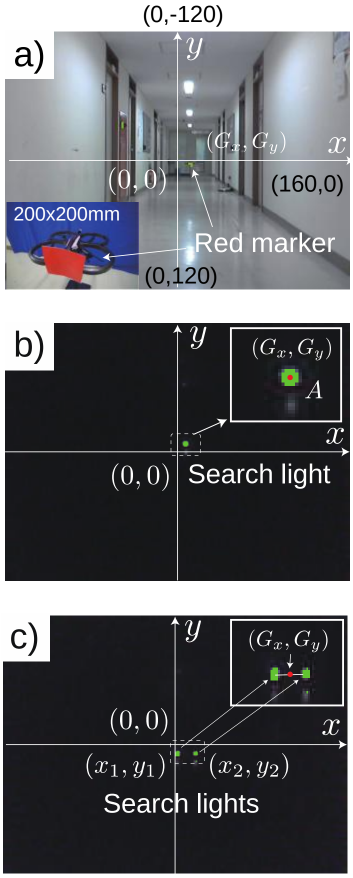

FIGURE 4: Camera image axis definition and image processing examples in the case of (a) 200×200 mm red fluorescent color and (b) single, (c) IR light intensity of two spotlights when the drone was positioned 15 m from the start position. The green areas show extracted red marker positions or IR luminance areas.

3.2 Experiment 2 and 3: Conditions for single or two IR spotlights positioned on the ground

In the following experiments, which were conducted to evaluate our proposed method, the spotlights(s) were used to measure the position of the drone instead of a red marker. The position of the drone could be calculated from the CoG of a "single" spotlight position $\overrightarrow{x_1} = (x_1, y_1)$and spotlight luminance Area A on the camera image (Fig. 4b). The horizontal and vertical position (x-y axis) of the drone is $\overrightarrow{x_1}$ and the distance z from the camera is calculated from the conversion function $z = g(A) \sim \frac{\alpha}{\sqrt{A}}$, which had been previously measured by using the geometric layout of the camera and Area A.

However, the drone position could also be calculated from the CoG positions of two spotlights $\overrightarrow{x_1} = (x_1, y_1)\overrightarrow{x_2} = (x_2, y_2)$ on the camera image (Fig. 4c). $\overrightarrow{x_0} = (\overrightarrow{x_1} + \overrightarrow{x_2})/2$ represents the horizontal and vertical position (x-y axes) of the drone. The rotation θ in the x-y plane was calculated from $\tan\theta = (y_2 - y_1)/(x_2 - x_1)$, and the distance z from the camera was calculated from $l = |\overrightarrow{x_2} - \overrightarrow{x_1}|$ and the conversion function $z = f(l)$, which had been previously measured using the geometric layout of the camera and the markers.

In Experiments 2 and 3, the two drone position measurement methods mentioned above were compared. The experimental setup is shown in Fig. 5. Here, the measurement stability of the distance z in cases when a single spotlight is used (Experiment 2) and cases when two spotlights are used (Experiment 3) is evaluated as the drone is traveling to a target 15 m away (0,15) and returning to the start position (0,0). In the single spotlight case (Experiment 2), the spotlight was positioned at $(0, -5)$. The green dot represents the start position and the two yellow dots are the spotlight position. In Experiment 3, the two spotlights were positioned at $(-0.5, -5)$ and $(0.5, -5)$ m relative to the drone flight start position of (0,0).

As with Experiment 1, the QVGA camera attached in the front of the drone was used for real-time position information measurement and control was performed based on the position and area of the target object (spotlight image) in the camera image within a 100 msec period.

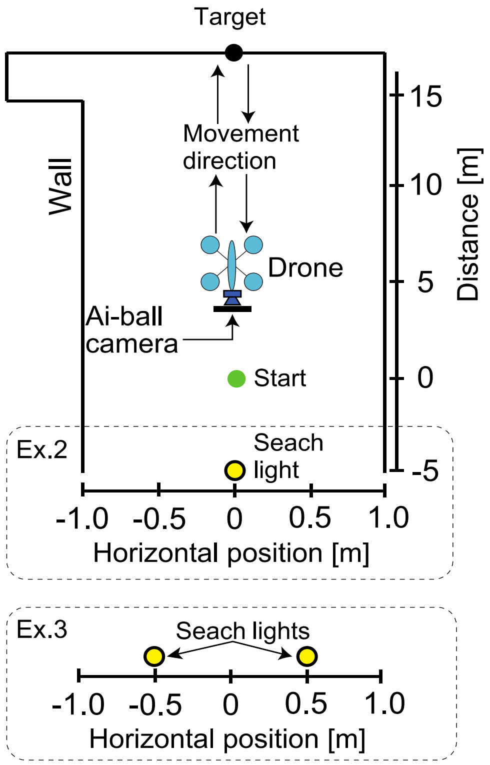

FIGURE 5: 15 m autonomous movement control distance experimental setup using single (Experiment 2) and two (Experiment 3) spotlights in an enclosed corridor

When the center of the two spotlight positions is $\overrightarrow{x_0} = \frac{\overrightarrow{x_1}+\overrightarrow{x_2}}{2} = (G_x, G_y)$, the drone's movement roll and pitch speed commands $V^r_{command}$,$V^p_{command}$ were same with Eq. (1). Simple proportional feedback was used in the experiment. Theγ_p used the 10% constant forward movement settings of the drone. The $\gamma_r$feedback parameters were determined using the same procedure as Experiment 1. The sign of parameter γ_p was changed when the drone reached the target distance of approximately 15 m (approximately 23 sec flight time).

3.3 Experiment 4: 15 m range round trip movement using two IR spotlights

In Experiment 4, the drone performed a 50 sec control task of traveling 15 m down an enclosed corridor and returning to the original position (Fig. 4) while using the two spotlights for feedback control.

IV. RESULTS AND DISCUSSION

Figure 6 shows the distance measurement results of a comparison between the red fluorescent marker and different colored markers (100 × 100 (blue), 150 × 150 (red), 200 × 200 (green) mm) when the fixed camera (C270, Logicool) was used during 15 m round trip movements in the corridor (Experiment 1 condition). The black line is the theoretical position determined by measuring from the two spotlight positions (Experiment 2 and 3 conditions). We found that the standard deviation (SD) of the estimated distance could be decreased by increasing the size of the red fluorescent marker. For example, in the timing of Period A (from 16 to 17 sec) of Fig. 6, the average and SD was as shown in Table 1. The real distance in Area A is approximately 10 m, and the estimated distances could be correctly measured by increasing the red marker area from 100 × 100 to 200 × 200 mm. Additionally, the SD could be decreased by increasing the red marker area. However, when the real distance increased to Area B (approximately 15 m, travel time from 20 to 25 sec), the estimation distances and SD began fluctuating and could not be stabilized because the red marker area appeared smaller than 10 dots in the camera view (Fig. 4b). As a result, the distance estimation process did not work well (Table 1). To estimate the distance by extracting the red marker area from the camera image, the marker area must be correctly measured in the image view, even when the marker area is small. In Experiment 1, as shown in Fig. 4a, the presence of numerous obstacles around the red marker position made it difficult to extract the red marker area.

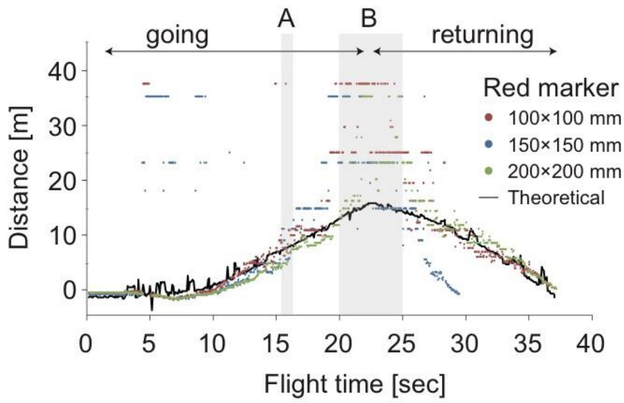

FIGURE 6. Distance measurement results in the case of 15 m round trip movement in the case of a red fluorescent marker. Red markers of various sizes (100 × 100, 150 × 150, 200 × 200 mm) were attached at the rearward facing side of the drone.

TABLE 1
ESTIMATED DISTANCES AND FLUCTUATIONS FROM FLUORESCENT RED MARKER AREA A OR B IN FIG. 6

Area A (10 m)	100×100 mm	150×150 mm	200×200 mm
Average [m]	16.0	15.4	11.9
S.D. [m]	2.26	0.69	0.47
Area B (15 m)	100×100 mm	150×150 mm	200×200 mm
Average [m]	26.1	36.0	31.9
S.D. [m]	8.68	10.99	9.29

Figure 7 shows the calculated distance results in cases when a single spotlight (red dots) and two spotlights (blue dots) were used during 15 m round trip movements. The vertical axis shows the calculated distance z [m] and the horizontal axis shows the flight time [sec]. The black line indicates the theoretical position of the drone as measured by the two spotlights positioned on the target side. In this experiment, the movement direction was changed at approximately 22 sec. The red dots (single spotlight) were difficult to calculate and unstable when the distance is approaching to 15 m when compared with the blue dots (two spotlights). In addition, z calculation errors of 18.6%were measured at odd intervals (area C) in the single spotlight (red dots) case. In the case of the two spotlights at the distance of 15 m, the SD was 0.31 m in the same area C. In addition, the distance S.D. at 15 m for a single spotlight was 10.6 m. Thus, it is clear that there were large distance measurement fluctuations in the single spotlights case. Table 2 shows Area C, which is the primary result of this study.

Based on the above experimental results, the two spotlights position measurement method works more effectively than the single spotlight method.

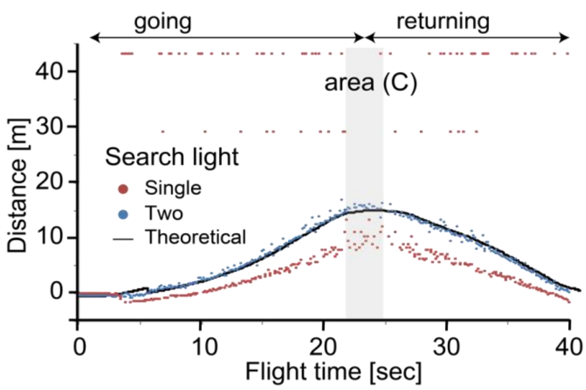

FIGURE 7: Distance measurement during 15 m distance autonomous control experiment using both single and two spotlights in an enclosed corridor.

TABLE 2
SINGLE AND TWO SPOTLIGHTS POSITION MEASUREMENT METHOD SHOWN IN FIG. 7

Area C (15 m)	Single spotlight	Two spotlights
Average [m]	13.9	15.7
S.D. [m]	10.66	0.31

As for Experiment 4, Fig. 8 shows the 50 sec 15 m round trip results for an enclosed corridor (same experimental conditions as Fig. 5). The blue and red dots indicate the outbound and returning trajectories, respectively. The green area period's position average and SD calculations are shown on the left side of the figure. Based on these results, the average and SD of the 15 m round trip control were calculated as –0.13 (± 0.06) m (outbound) and 0.09 (± 0.02) m (return).

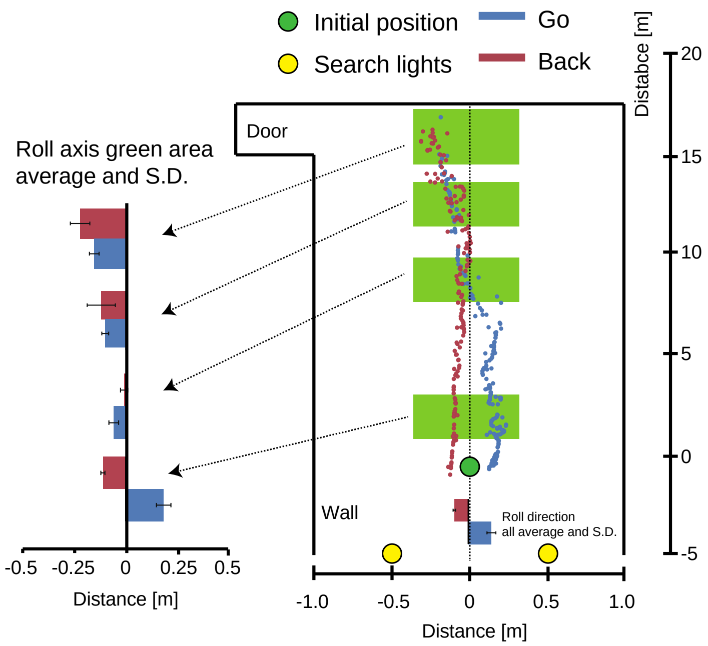

FIGURE 8: 15 m distance autonomous control experiment using two spotlights in an enclosed corridor.

As shown in the left bottom of Fig. 4a, even when the red marker size was large (200 × 200 mm) and the drone size was large (approximately 500 × 500 × 50 mm), the extracted red marker area at a distance of 15 m distance only measured from six to 10 dots in size. This appears to be the limit to the estimation distance when using a red marker attached to a drone moving straight ahead under constant floor lighting conditions in a university corridor. If the drone were to be moved outdoors, the distance estimation performance would deteriorate. In addition, we found that the large board red marker tended to destabilize the flight performance of the drone due to wind resistance, even when 10% forward or backward movement power was applied. One potential solution to the issue of reduced image size might be to use a higher resolution camera. However, the destabilization that results when attaching a large red marker board to the drone would still be unacceptable, especially in long distance inspections at sites such as bridges or tunnels.

One of the advantages of our proposed method is that the spotlight points are easy to find using bright IR regions. In addition, although misidentifications are possible if the sun is present in the camera image, positioning the spotlights on the ground makes it possible to use the accelerometer to ascertain the direction of gravity, and thus distinguish the spotlights from the sun.

V. CONCLUSION

In this paper, a 10 m-range autonomous four-rotor helicopter (drone) movement control system that utilizes two high-power spotlights was proposed and autonomous flight test evaluations were performed. To realize drone flights in excess of 10 m under unstable GPS signal situations, such as under bridges or inside tunnels during periodic maintenance inspections, the ability of a drone to perform correct self-positioning measurements is indispensable for stable control. In our experiments, distance measurements were more stable when two spotlights were used in comparison to experiments conducted with a single spotlight and those conducted with a red marker attached to the drone. And the 15-m-long distance measurement precision of the drone position shows an SD of 0.31 m. Our proposed method would be effective in situations where no skilled drone control operator is available and when flights requiring visual confirmation under adverse conditions are required.

ACKNOWLEDGEMENTS

This work was supported by KouheiFujiuti, Shuichi Honda, Hiroaki Takano.

REFERENCES

[1] K. Nonami, F. Kendoul, S. Suzuki, W. Wang, D. Nakazawa, "Autonomous flying robots : unmanned aerial vehicles and micro aerial vehicles," Springer Japan. 2010.

[2] Ministry of Land (Japan), Infrastructure and Transport, bridge maintenance Subcommittee, Liang maintenance technology site verification and evaluation of the results, March 19, 2015: Available from: http://www.mlit.go.jp/common/001083014.pdf (URL)

[3] E. Altug, J. P. Ostrowski, C. J. Taylor, "Control of a quadrotor helicopter using dual camera visual feedback," International Journal of Robotics Report, vol.24, no.5, 2005, pp. 329-341.

[4] B. Ludington, E. Johnson, G. Vachtservanos, "Augmenting UAV autonomy: vision-based navigation and target tracking for unmanned aerial vehicles," IEEE Robotics and Automation Magazine, vol.13, no.3, 2006, pp. 63-71.

[5] H. Takano, H. Toda, "Roll movement realized by yaw and roll command combination method of AR Drone 4 rotor helicopter for improving stability of automatic position stop," International Conference on Advanced Mechatronics (ICAM 2015), Waseda University, Tokyo, Japan, Dec.5-8, 2015, pp. 53.

[6] H. Toda, S. Honda, H. Takano, "Effectiveness of Fast Speed Yaw and Roll Control Switching Instead of Normal Roll Control for AR Drone 4 rotor Helicopter," International Journal of Innovative Research in Advanced Engineering, vol. 3, issue 7, JYAE10081, doi:10.17632/y52bmbgtkg.1., 2016.

[7] H. Toda, H. Takano, "Effect of Discrete Yaw Direction Setting for 4 Roter Helicopter Control: Computer Simulation and AR. Drone Model Implementation," International Journal of Innovative Research in Advanced Engineering, vol. 3, issue 7, JYAE10086, doi:10.17632/cj8f3v6csr.1., 2016.

[8] S. Honda, H. Toda, M. Kitani, G. Capi, "Development of small size 4 rotor helicopter automatic position control algorithm", 32nd Annual Conference of the Robotics Society of Japan, 1D3-01, 2013.

[9] S. Honda, H. Toda, M. Kitani, G. Capi, "Development of 4 rotor automatic flight control system using image processing filters that can be self-position estimation in natural objects with the aim of the reactor building spot," ROBOMECH 2014, March, Toyama, 2014.

[10] S. Azrad, F. Kendoul, K. Nonami, "Visual Servoing of Quadrotor Micro-Air Vehicle Using Color-Based Tracking Algorithm," Journal of System Design and Dynamics (JSME), vol. 4, no. 2, 2010, pp. 255-268.

[11] B. Ludington, E. Johnson, G. Vachtservanos, "Augmenting UAV autonomy: vision-based navigation and target tracking for unmanned aerial vehicles," IEEE Robotics and Automation Magazine, vol. 13, no. 3, 2006, pp. 63-71.

[12] K. Nonami, "Rotary Wing Aerial Robotics," Journal of Robotics Society of Japan, vol. 24(8), 2006-11-15, pp. 890-896.

[13] J. Engel, J. Sturm, D. Cremers, "Camera-based navigation of a low-cost quadrocopter," Intelligent Robots and Systems (IROS), 2012.

[14] R. Mahony, T. Hamel, "Image-based visual servo control of aerial robotic systems using linear image features," IEEE Trans. on Robotics, vol.21, no.2, 2005, pp. 227-239.

[15] Y. Kubota, T. Iwatani, "Dependable visual servoing of a small-scale helicopter with a wireless camera," 15th International Conference on Advanced Robotics (ICAR), 20-23 June 2011.

[16] T. K. Roy, M. Garratt, H. R. Pota, M. K. Samal, "Robust altitude control for a small helicopter by considering the ground effect compensation," 10th World Congress of Intelligent Control and Automation (WCICA), DOI:10.1109/WCICA.2012.6358168, 2012, pp. 1796-1800.

[17] O. Andrisani, E. T. Kim, J. Schierman, F. P. Kuhl, "A nonlinear helicopter tracker using attitude measurements," IEEE Transactions on Aerospace and Electronic Systems. vol.27, issue: 1, DOI:10.1109/7.68146, 1991, pp. 40-47.

[18] F. Chen, B. Jiang, F. Lu, "Direct adaptive control of a four-rotor helicopter using disturbance observer," International Joint Conference on Neural Networks (IJCNN), 2014, pp. 3821-3825.

[19] A. C. Satici, H. Poonawala, M. W. Spong, "Robust Optimal Control of Quadrotor UAVs," IEEE Access. 2013, vol. 1, DOI:10.1109/ACCESS.2013.2260794, 2013, pp. 79-93.

[20] J. Toledo, L. Acosta, M. Sigut, J. Felipe, "Stability Analisys of a Four Rotor Helicopter," Automation Congress 2006, WAC '06. World, 2—6, pp. 1-6.

[21] P. Castillo, A. Dzul, R. Lozano, "Real-time stabilization and tracking of a four-rotor mini rotorcraft," IEEE Transactions on Control Systems Technology, vol. 12, issue: 4, DOI:10.1109/TCST.2004.825052, 2004, pp. 510-516.

[22] O. Meister, N. Frietsch, C. Ascher, G. F. Trommer, "Adaptive path planning for a VTOL-UAV," Position, Location and Navigation Symposium, 2008 IEEE/ION, DOI:10.1109/PLANS.2008.4570046, 2008, pp. 1252-1259.

[23] L. Garcia-Delgado, A. Dzul, V. Santib, M. Llama, "Quad-rotors formation based on potential functions with obstacle avoidance," Control Theory and Applications, IET, vol. 6, issue:12, DOI:10.1049/iet-cta.2011.0370, 2012, pp. 1787-1802.

[24] F. Kendoul, Z. Yu, K. Nonami, "Embedded autopilot for accurate waypoint navigation and trajectory tracking: Application to miniature rotorcraft UAVs," IEEE International Conference on Robotics and Automation, 2009. ICRA '09, DOI:10.1109/ROBOT.2009.5152549, 2009, pp. 2884-2890.

[25] K. Nomura, "Industrial applications type electric multi-rotor helicopter," introduction of mini-surveyor and flight demonstration. Mini-surveyor consortium: Available from http://mec2.tm.chiba-u.jp/ ~nonami/ consortium/ outline.html/ (url)

[26] E. Altu, J. P. Ostrowski, R. Mahony, "Control of a Quadrotor Helicopter Using Visual Feedback," Proceedings of the 2002 IEEE International Conference on Robotics and Automation, Washington DC, May 2002.

[27] Y. Yoshihara, K. Watanabe, T. Iwatani, K. Hashimoto, "Image-based visual servo control for a micro helicopter under partial occlusions," Proceedings of 2007 JSME Conference on Robotics and Mechatronics, ID 2A2-A06, Akita, Japan, May 10-12, 2007.

[28] K. Watanabe, Y. Iwatani, N. Kenichiro, K. Hashimoto, "A vision-based support system for micro helicopter control," Proceedings of the 2008 Conference on Robotics and Mechatronics, ID 1P1-F13, Nagano, Japan, June 5-7, 2008.

[29] Y. Kubota, T. Iwatani, "Dependable visual servoing of a small-scale helicopter with a wireless camera," Proceedings of the 2008 Conference on Robotics and Mechatronics. ID 1A2-O15, Okayama, Japan, May 26-28, 2011.

[30] S. Yoshida, Engneeringnavi. library of ARDroneForP5: Available from http://kougaku-navi.net/ARDroneForP5/ (URL).