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Vision-Based Guidance Control of a Small-Scale Unmanned Helicopter

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Abstract— **This paper describes vision-based guidance control of a small-scale unmanned helicopter. In previous research, helicopters were usually controlled by sensors such as GPSs and gyros. However, it is difficult to mount those sensors on small-scale helicopters that have little payload. Accordingly, small lightweight cameras were used to control the helicopter in this research. The applications of the cameras are for observation of the environment and the measurement of the position and attitude of the helicopter. The system of mounted cameras on the helicopter is useful for an indoor surveillance system using the helicopter as a mobile camera. The efficacy of the constructed system was verified through experimentation of automatic hovering control and guidance control.**

I. INTRODUCTION

Helicopters have superior flight characteristics such as vertical take-off and landing, hovering and slow flight. Automatic operation of small-scale unmanned helicopters is useful for flight operation and has drawn concern from a lot of researchers[1]-[7]. Some research results of small-scale unmanned helicopters have shown practical applications such as crop-dusting and inspections of power cables. In previous works, the cameras mounted on the helicopter were used for the purpose of observation and other sensors, such as GPSs and gyros, were used for guidance control. Many sensors are required to control helicopters that have enough payload. Conversely, small-scale helicopters which can not have much payload require a proper selection of sensors for automatic control. Vision is highly useful for flight operation and small-scale helicopters with vision systems have been studied in recent years [5]-[8].

In this research, vision-based position control and attitude control using a small-scale RC helicopter that has small lightweight cameras without either a GPS or a gyro are used. The small-scale helicopter is susceptible to disturbances, such as wind and weather. Accordingly, we intend to apply the helicopter to an indoor environment and use it as an indoor surveillance system. The helicopter is controlled based on the image information captured by the mounted cameras. A fundamental system was constructed and the efficacy was verified through experimentation of automatic hovering control and guidance control.

II. CONTROL SYSTEM

The control system of a small-scale unmanned helicopter is shown in Fig. 1. Two small lightweight radio transmission cameras were mounted on the helicopter. They can capture an image by 33[msec], 30[fps] and the weight of vision system is about 30[g]. The directions of each camera were parallel and perpendicular to the direction of the heading, respectively. Also, in the directions of each optical axis of the camera, the markers were set in the positional relation as shown in Fig. 1. The helicopter was controlled to hover in the place where these two markers were in the center of the image planes of each camera, using the image information only. The control flow of whole system is as follows:

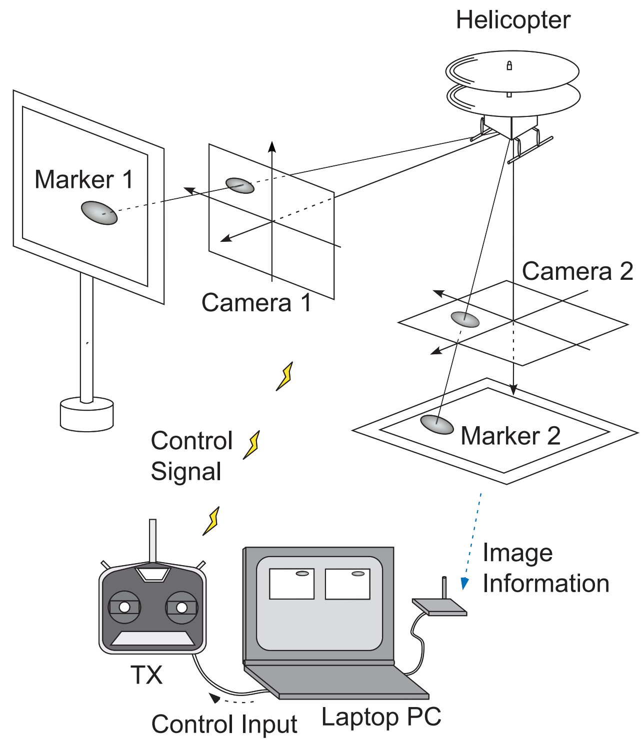

Fig. 1. Control system of a small-scale unmanned helicopter

1. The image information of the camera was transmitted to the laptop PC.
2. The control inputs were calculated from the image information (binarization and calculation of the center of gravity of the marker) and were output to the TX through a DA converter card connected to the laptop.
3. The control inputs (voltages) were transmitted to the helicopter as a pulse signal using the TX.
4. The helicopter was controlled to hover in the place where the markers were kept close to the center of the image planes.

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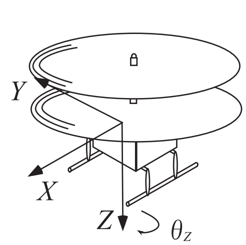
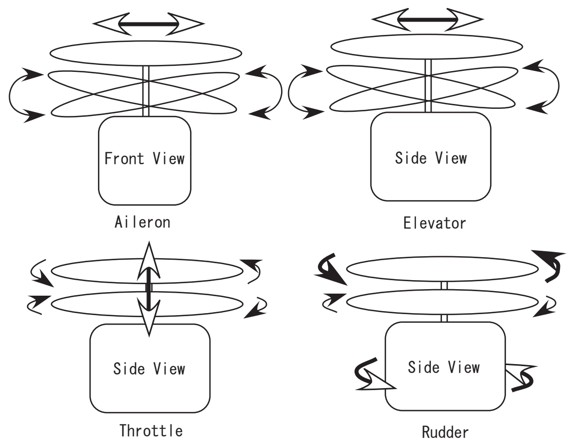
(a) Photo



(b) Coordinate system



(c) Explanation of movement

Fig. 2. Schematic of a co-axial contra-rotating rotor helicopter

The desired hovering control is achieved by repeating procedures 1 to 4 above.

According to Fig. 2, the motion mechanism of the helicopter is described as follows: the helicopter has upper and lower rotors that counter-rotate co-axially to negate reverse torque[9]. The co-axial contra-rotating system is complex and of inferior maintenance and mobility than other flight mechanisms. However, the helicopter has the ability to hover in a horizontal attitude and it is highly stable. The throttle for the motion of the vertical direction (the Z axis) generates lift force by changing the rotating speeds of the upper and lower rotors. The aileron and the elevator, horizontal motion (the Y axis) and forward to backward motion (the X axis) respectively, are controlled by the axial tilt of the lower rotor. The rudder for the rotation around the Z axis, generates rotational torque by the difference of the rotating speeds of upper and lower rotors.

In Fig. 3, the images gained by the mounted cameras and the motion of the helicopter are shown. The control input for the throttle is calculated by the y coordinate, y_{c1} of the center of gravity of Marker 1 in the image plane of Camera 1. The control inputs for the aileron, the elevator and the rudder are calculated by the x, y coordinates, x_{c2}, y_{c2} of the center of gravity of Marker 2 and the tilt of the principal axis of inertia of the ellipse in the image plane of Camera 2.

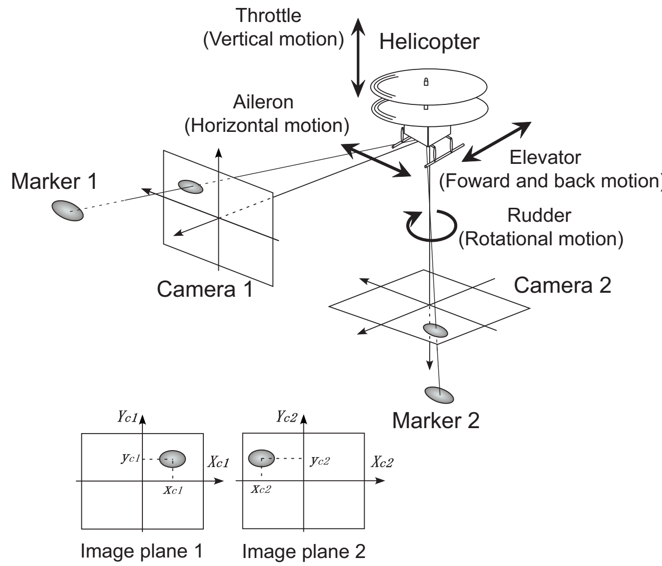


Fig. 3. Motion of the helicopter based on visual information

III. Control system design of the helicopter based on manual control experimentation

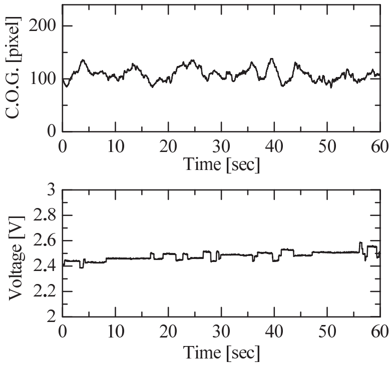
It is difficult to derive the mathematical model of the co-axial contra-rotating rotor helicopter. Accordingly, the control system was designed based on system identification or manual control experimentation in previous research[7]. It seems possible to derive a proper model by executing system identification experimentation in this research. However, it was difficult to gain proper input-output data for system identification because of noise interference from the radio transmission camera. Consequently, the control system was designed from the result of manual control experimentation.

A. Input-output data of manual control experimentation

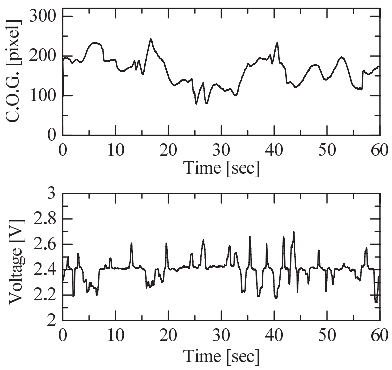
The procedure to gain input-output data of manual control experimentation is described as follows: Using the experimental system shown in Fig. 1, the helicopter was controlled to hover in the place where the markers were kept close to the center of the image planes of the two cameras. Then, the variations of voltages of four input values, the throttle, the aileron, the elevator and the rudder of TX were measured. The variations of the center of gravity of the markers and the tilt of the principal axis of inertia of the ellipse in the image planes were obtained, simultaneously. The input-output data from manual control experimentation gained by the above procedure is shown in Fig. 4. The variations of the aileron and the elevator were great, however, the variations of the throttle and the rudder were stable without changing control inputs. From these results, maximum and minimum control input values (voltages) in manual control were recorded. These values were used to design the automatic control system.

B. Control systems of throttle, aileron and elevator

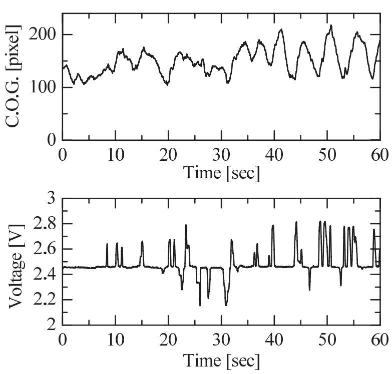
The marker's coordinate of the center of gravity in the image plane was used to design the velocity control system.



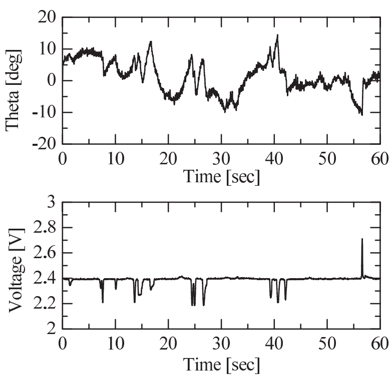
(a) Time variation of throttle



(b) Time variation of aileron



(c) Time variation of elevator



(d) Time variation of rudder

Fig. 4. Time variations of input-output data

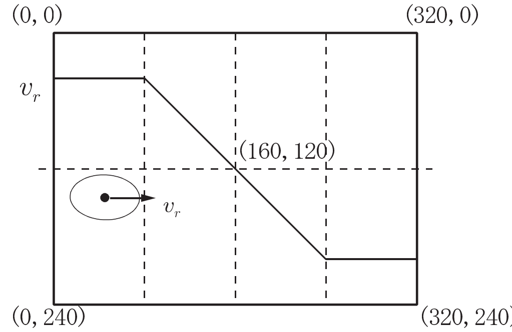


Fig. 5. Schematic of velocity control algorithm (aileron)

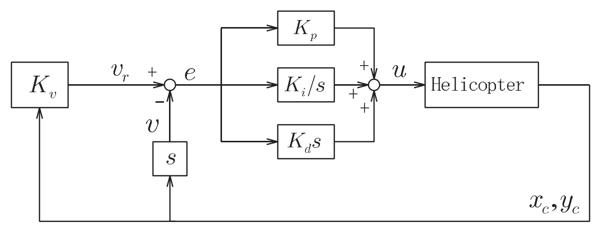


Fig. 6. Block diagram of control system

The image plane of the camera is shown in Fig. 5 and the size is 320×240 [pixels]. It is divided into four regions and the proper desired velocity v_r is given according to the region where the center of gravity of the marker is contained. For vision-based control, it is very important that the velocity setting is adjusted to keep the marker in the field of view of the camera [10]. The desired velocity is given as the moving velocity of the coordinate of the marker's center of gravity in the image plane. For helicopter control, the method of image-based visual feedback only needs variations of feature quantities in the image plane. Three-dimensional position information is not needed.

When the center of gravity of the marker is *far* from the center of the image, the control system adjusts the constant desired velocity to bring the center of gravity back to the center of the image. When it is *close* to the center of the image, the desired velocity converges to zero proportionally. The target value tracking control is executed for the desired velocity v_r given above by the PID controller. The block diagram is shown in Fig. 6, where $\boldsymbol{K}_p$, $\boldsymbol{K}_i$, $\boldsymbol{K}_d$ are a proportional gain, an integral gain and a differential gain, respectively, and $\boldsymbol{K}_v$ is a changing gain to determine the desired velocity.

C. Rudder control system

The rudder input controls the rotation around the Z axis of the fuselage and the attitude control is executed from the tilt of the principal axis of inertia of the marker ellipse in the

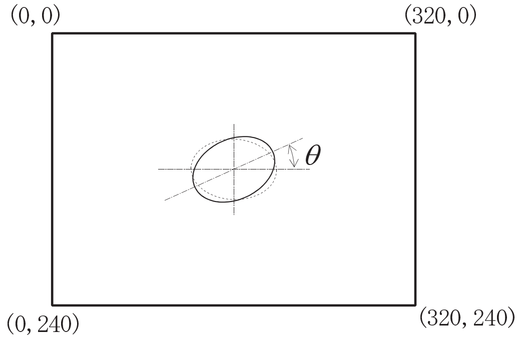


Fig. 7. Schematic of angle control algorithm

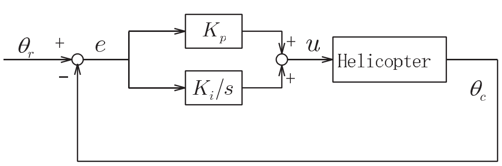


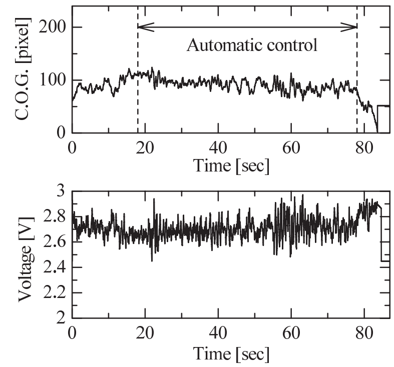
Fig. 8. Block diagram of control system

image planes of the downward-pointing camera. As shown in Fig. 7, the tilt of the principal axis of inertia, θ is controlled to follow the desired angle θ_r in order to keep the direction of the fuselage constant. The block diagram is shown in Fig. 8.

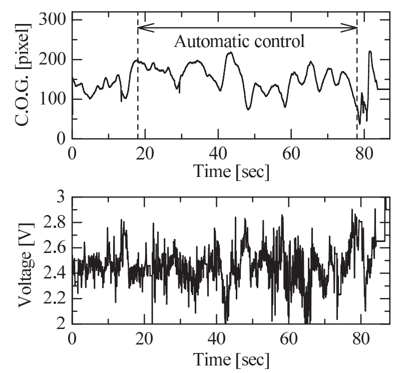
IV. Automatic hovering control experimentation based on visual information

A four axes-automatic hovering control experiment was performed. Each parameter of the PID controller described in the previous section was adjusted based on the input-output data gained by manual operation experimentation.

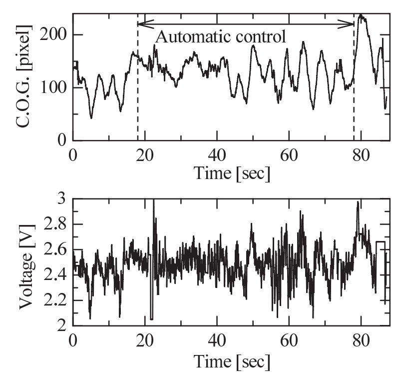
At first, the helicopter was controlled in a position where the two markers were captured in the image planes manually, and then automatic control was executed. The time variations of the center of gravity of the markers and the tilt of the principal axis of inertia of the marker ellipse in the image planes as well as input values of the voltage are shown in Fig. 9. Automatic control was performed for about 60 seconds from 18 to 78 [sec], while the markers were kept close to the center of the image planes and the angle, θ was kept close to zero. In Fig. 10, the variation of the position of the center of gravity in the image plane captured by the downward-pointing camera is shown. In this figure, the point where the two dashed lines bisect at right angles is the center of the image plane and the helicopter is located immediately above the marker. The solid line represents the path of the helicopter during automatic control. In this experimentation, the objective is to keep the helicopter hovering within a spherical area 70[cm], which is twice the size of the rotor,



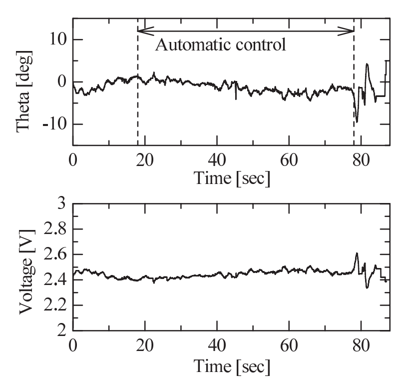
(a) Time variation of throttle



(b) Time variation of aileron



(c) Time variation of elevator



(d) Time variation of rudder

Fig. 9. Time variations of input-output data

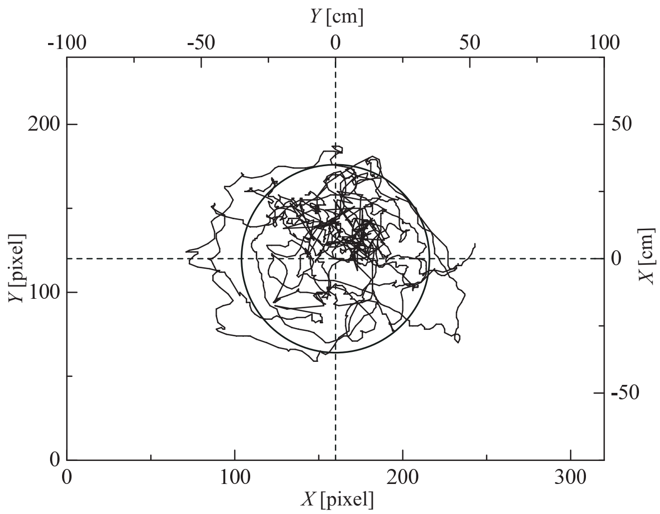


Fig. 10. Experimental result of hovering control

about 35[cm]. The path of helicopter was kept in the circle, and the helicopter performed the desired hovering [11].

V. Automatic guidance control experimentation based on visual information

In the previous section, the desired hovering control was performed and automatic guidance control experimentation was demonstrated using the same controller.

A. Algorithm of guidance control

Four markers were placed in forward and downward directions against the helicopter shown in Fig. 11 and the helicopter was controlled to move from Marker A to Marker B. The images of the downward-pointing camera are shown in Fig. 12. In guidance control, the motions in the directions of the X and the Z axes and the rotation around the Z axis were controlled using the same method as the hovering control. The control of the motion in the direction of the Y axis was changed as follows: The helicopter was controlled to hover in the place where Marker A was kept in the center of the image plane shown in Fig. 12(a) for a given time (*State 1*). After that, the helicopter was controlled to move to the way point between Marker A and Marker B by changing the desired position of Marker A from the center to the left in the image plane as shown in Fig. 12(b) (*State 2*). Then, the desired position was changed from Marker A to Marker B as shown in Fig. 12(c) (*State 3*). Finally, the helicopter was controlled to hover in the place where Marker B was kept in the center of the image plane shown in Fig. 12(d) for a given time (*State 4*). The desired guidance control between the two markers was performed according to the above procedure. Moreover, extensive guidance control can be constructed using multiple markers.

B. Experimental result

In guidance control experimentation, the helicopter was controlled as the position where Marker A was kept in the center of the image plane manually, and then the helicopter switches control automatically. In the experimentation, automatic control was performed for about 35 seconds from 5 to 40 [sec]. After that, the helicopter was switched to manual control to prepare for landing.

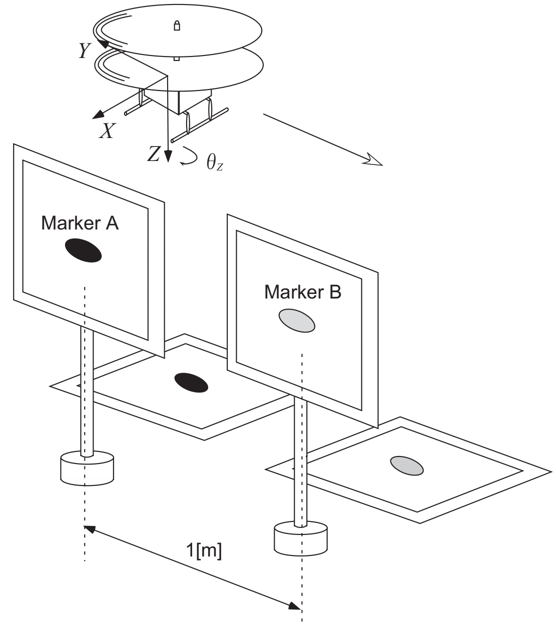
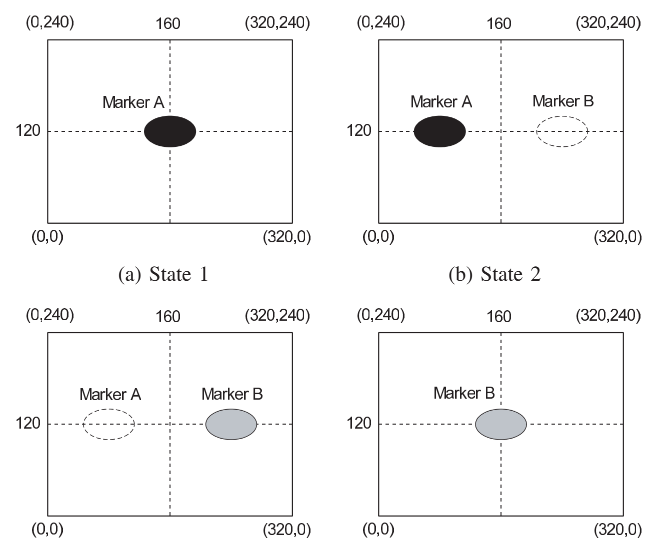


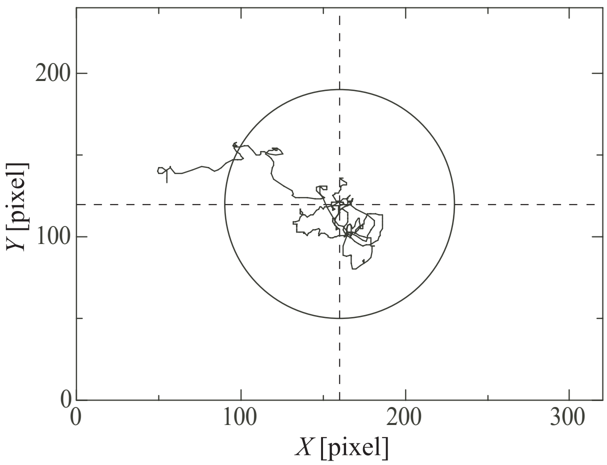
Fig. 11. Coordinate system



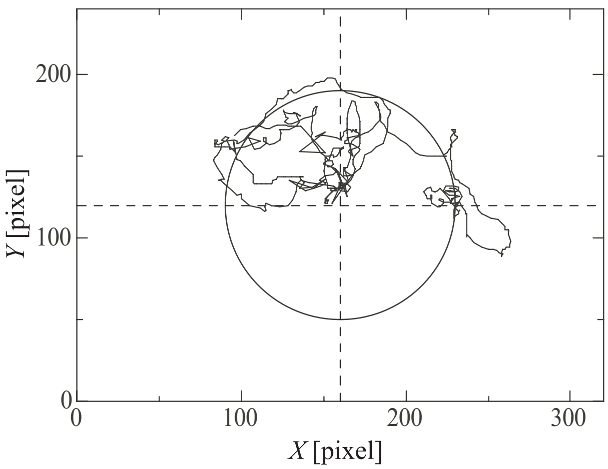
(a) State 1 (b) State 2 (c) State 3 (d) State 4

Fig. 12. Schematic of guidance control algorithm

In Fig. 13, the variations of the position of the center of gravity in the image plane, captured by the downward-pointing camera, are shown. Figure 13(a) and (b) represent the motion of the helicopter from *State 1* to *State 2* and from *State 3* to *State 4*, respectively. Moreover, Fig. 13(a) and (b) are overlapped in Fig. 14 and these results show that the helicopter was controlled from Maker A to Maker B properly using the guidance control algorithm [12].



(a) State 1 → 2



(b) State 3 → 4

Fig. 13. Experimental results of guidance control

VI. CONCLUSION

In this paper, vision-based guidance control of a small-scale unmanned helicopter was examined. The basic system was constructed and the efficacy was verified through experimentation. At first, the helicopter was controlled to hover in a position where the two markers were captured close to the center of the image planes. From the experimental result, the accuracy of the hovering control was enough to extend guidance control. Accordingly, the guidance control from one marker to another was performed properly using an extended algorithm. However, the environment of experimentation was regulated for the vision system and it is required to examine the efficacy of the constructed system under real environmental conditions. In order to control the helicopter, how to extract proper image information in the real environment is very important. Moreover, actual applications of the small-scale unmanned helicopter are considered in our future work, such as a mobile camera for inspection or surveillance.

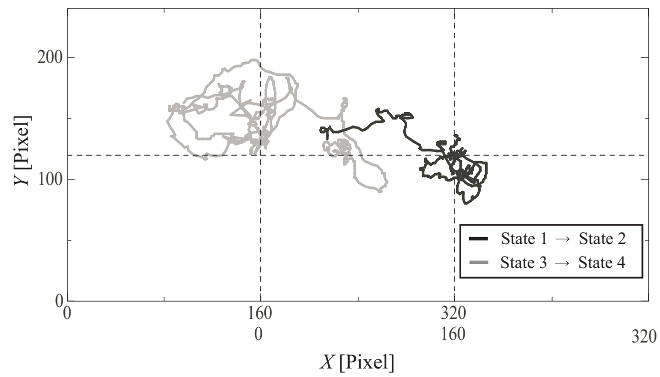


Fig. 14. Experimental result of guidance control from Marker A to B

VII. ACKNOWLEDGMENTS

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