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An Implementation of Drone-Projector: Stabilization of Projected Image

Eunbin Choi, Younghyeon Park, and Byeungwoo Jeon; Department of Electrical and Computer Engineering, Sungkyunkwan University; Suwon, South Korea

Abstract

A drone-projector equipped with a beam projector mounted on a drone has been investigated in order to develop a projector which can overcome restriction of place on which an image is projected. For the stability, the drone-projector requires its mass to be centered, and the additional weights related to projector should be within the payload of the drone. In addition to this requirement, the drone-projector should be designed to minimize the distortion of image caused by 3D translations or rotations of a drone during its hovering due to vibration of propellers, or global positioning system (GPS) errors. In this paper, we consider rotation of a drone-projector which makes the projected image tilted, keystoned, and shifted. To overcome this problem, we propose a software-based stabilization method which pre-corrects the image to be projected based on flight information. Our experimental results show that the distortion of the projected image due to rotations of the proposed drone-projector is attenuated by applying our stabilization method.

Introduction

A quadrotor-based flying object without a human pilot aboard, simply referred to as a drone, can be used in places where people cannot easily approach such as in case of forest fire monitoring or disaster relief. On the other hand, a beam projector is able to share images in a large projection display. In this paper, we are interested in designing a drone-projector which mounts a projector on a drone in order to make the projector flying. The drone-projector can be utilized as a digital signage display providing useful information or advertisement by projecting an image on projection surfaces such as outer wall of building and arbitrary objects. Fig. 1 illustrates such a conceptual usage of projection onto outside wall of building.

One issue of the drone-projector as a moving display is the distortion in the projected image due to 3D translation and rotation of a drone. Even in hovering, a drone has such motions due to vibration of propeller motors or global positioning system (GPS) error. In this paper, we particularly focus on rotation of the drone-projector while in hovering, which makes the projected image tilted, keystoned, and shifted. It is noted that a similar problem existing also in stabilizing a shooting camera mounted on a drone in flight is usually solved by employing a gimbal working as a mechanical stabilization equipment. However, when it comes to our problem of designing a drone-projector, the gimbal makes not only our system heavier but also our system become more complicated [1]. Thus, in this paper, we investigate a software-based stabilization method based on a mathematical model employing a perspective projection transformation matrix from the concept of camera calibration [2].

Early research had focused on how to create the hardware configuration of the drone-projector. J. Scheible et al. [3] designed a drone-projector system which is equipped with a carbon fiber frame with approximately 75 cm diameter, and it weighs 4 kg. However, they did not research on stabilization of the projected image by the drone-projector [3]. Y. Hosomizo et al. [4] proposed a method for stabilizing image fluctuation by applying geometric transformation to original images before projection. In their stabilization method, the parameters required for the transformation are computed by the estimated position and orientation of the projector by combination with dead reckoning [5] and computer vision techniques [6] to reduce accumulation errors while achieving real-time processing. But, they [4] used server PC via wireless communication for computation, and it did not consider the distance from the drone-projector to projection surface. W. A. Isop et al. [7] proposed a laser projection system enabling in-flight projection with feedforward correction for stabilization of projected images with small semi-autonomous micro aerial projector (MAP) based on pose estimates of an Optitrack motion tracking system. They [7] presented an example where MAP assists a student solving mathematical problems by projecting results. However, their system [7] was dependent on the motion tracking system based on eight tracking cameras, which is constrained to place.

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Figure 1. A conceptual usage of projecting an image onto an exterior wall of building.

The contribution of this paper is as followings. We propose a sensor-based stabilization method that allows the drone-projector to fly anywhere without experimental environment requirements such as camera installation. The stabilization method is modeled geometrically by estimating how the drone-projected image will change when the drone is rotating: the projected image is tilted and keystoned, and it can be also shifted.

The remainder of this paper is organized as follows. We first describe the hardware configuration of the proposed drone-projector and introduce the geometrical model for stabilizing the projected image. To evaluate the performance of the proposed stabilization method, we carry out an image projection test using the proposed drone-projector and compare the distortions of projected images between stabilization-ON and OFF. At the end of the paper, we conclude this paper with comments on possible future works.

Proposed Method

System Description

The proposed drone-projector mainly consists of a small drone without a camera and a digital light processing (DLP) projector. To compensate the distortions in the projected image by the 3D rotations of the drone-projector, the rotation angles and distance of the drone-projector to a projection surface are obtained by AHRS (attitude and heading reference system) and LiDAR (light detection and ranging) sensors which are additionally mounted on the drone-

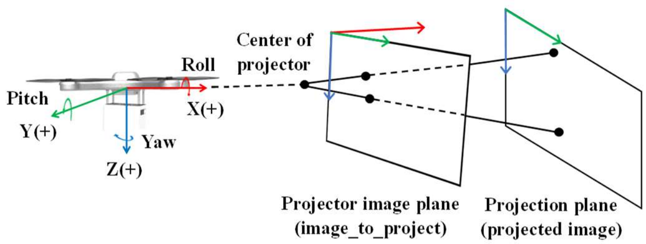


Figure 2. The defined coordinate system of the drone-projector.

projector. A computation board on the drone estimates the parameters of a stabilization model to pre-distort the projected image according to a geometrical model supplied by the two-sensor data. A DLP projector is connected to the board with high definition multimedia interface (HDMI) cable.

Stabilization of Projected Image

The projected image by the drone-projector is distorted by drone movements such as 3D translations and rotations even during hovering because of vibration of propeller motors or GPS error. In this paper, we mainly focus on the 3D rotations of the drone-projector which makes the projected image tilted, keystoned, and shifted. A transformation model H to define the rotations of the drone-projector is introduced as below:

$$X_w \cong HX_i \qquad (1)$$

where X_i and X_w are matching spatial locations respectively in a undistorted (3D projector image plane) and a distorted image (2D projection plane). The coordinate system of the drone-projector (which is the same as that of the drone) is in Fig. 2 in which x-, y-, and z-axis directions respectively correspond to forward, right, and downward movements. They are also consistent respectively to roll-axis, pitch-axis, and yaw-axis rotations. Accordingly, the projected image only has y- and z-axis because of projection in the direction of the x-axis. Therefore, Eq. (1) can be rewritten as:

$$[y_w,\ z_w,\ 1]^T \cong H \cdot [y_i,\ z_i,\ 1]^T \qquad (2)$$

where $[y_i, z_i, 1]^T$ and $[y_w, z_w, 1]^T$ respectively represent points in a undistorted and a distorted image. The transformation model H which considers the rotations of the drone-projector can be represented by:

$$\begin{aligned} &H = (H_{intrinsic} H_{rotation}) \circ H_{unit} \\ &where\ \ H_{rotation} = H_{roll} H_{pitch} H_{yaw} \end{aligned} \qquad (3)$$

where $H_{rotation}$ is a rotation matrix which makes the projected image tilted, keystoned, and shifted, and $H_{intrinsic}$ is an intrinsic parameters matrix specifying the projector. H_{unit} is a unit matrix for converting the unit of the translation parameters estimated from flight information (cm) denoting the movement of the drone-projector into the unit of the projected image (pixels). H_{unit} is element-wise multiplied by Hadamard Product $\circ$ as in Eq. (3).

$$H_{intrinsic} = \begin{bmatrix} f_y & 0 & c_y \\ 0 & f_z & c_z \\ 0 & 0 & 1 \end{bmatrix}$$

$$H_{rotation} = \begin{bmatrix} r_{11} & r_{12} & t_y \\ r_{21} & r_{22} & t_z \\ r_{31} & r_{32} & t_x \end{bmatrix} \qquad (4)$$

$$H_{unit} = \begin{bmatrix} 1 & 1 & \alpha \\ 1 & 1 & \alpha \\ 1 & 1 & 1 \end{bmatrix}$$

where f_y and f_z are respectively the horizontal and the vertical focal lengths. They can be replaced by f because they have a similar value for the projector recently manufactured. (c_y, c_z) indicates the central point of the projected image. H_{unit} has a proportional coefficient α to unify the units, and it can be calculated by dividing the spatial resolution of the projection area (in pixels) by the height of the projection area (in cm). The rotation matrix $H_{rotation}$ has rotation parameters r_{11}, r_{12}, r_{21}, r_{22}, r_{31}, r_{32} which can be derived from the well-known 3D rotation matrix, and translation parameters t_y, t_z. In roll-axis rotation, the translation parameters are required here because the projector is located off-center of the rotations. Thus, the of the drone also causes vertical and horizontal shift, and in case of pitch- and yaw-axis, the rotations itself have a characteristic to shift the central point.

Moreover, the rotation parameters of the rotation matrices in roll-axis H_{roll}, pitch-axis H_{pitch}, and yaw-axis H_{yaw} can be rewritten by the well-known 3D rotation matrix by:

$$H_{roll} = \begin{bmatrix} \cos(\theta_{roll}) & -\sin(\theta_{roll}) & t_{y_{roll}} \\ \sin(\theta_{roll}) & \cos(\theta_{roll}) & t_{z_{roll}} \\ 0 & 0 & 1 \end{bmatrix}$$

$$H_{pitch} = \begin{bmatrix} 1 & 0 & t_{y_{pitch}} \\ 0 & \cos(\theta_{pitch}) & t_{z_{pitch}} \\ 0 & \sin(\theta_{pitch}) & 1 \end{bmatrix} \qquad (5)$$

$$H_{yaw} = \begin{bmatrix} \cos(\theta_{yaw}) & 0 & t_{y_{yaw}} \\ 0 & 1 & t_{z_{yaw}} \\ -\sin(\theta_{yaw}) & 0 & 1 \end{bmatrix}$$

where θ_{roll}, θ_{pitch}, and θ_{yaw} are rotation angle values in roll-axis, pitch-axis, and yaw-axis, respectively. However, the translation parameters t_y, t_z in the rotations matrix are required to be

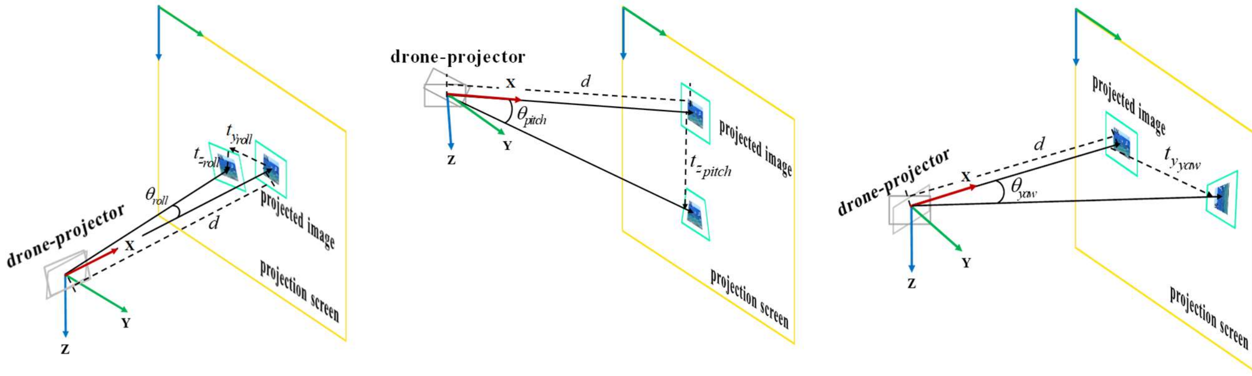


Figure 3. The geometrical models of the translation parameters. (a) The model for roll-axis. (b) The model for pitch-axis. (c) The model for yaw-axis.

estimated to stabilize the projected image by the drone-projector based on flight information. In our prior work [8], in order to calculate the translation parameters, t_y , t_z , the degree of movement of the central point of the projected image was manually measured and stored in a look-up table (LUT) when the drone-projector has rotations. However, in this paper, we improve our research [8] by geometrically modeling the translation parameters based on flight information.

Fig. 3 depicts the geometrical models to estimate the translation parameters for the roll, pitch, and yaw-axes where the translation parameters are defined by t_y and t_z , and d is the distance of the drone-projector to projection surface. Fig. 3(a) shows the geometrical model for roll-axis rotation. The translation parameters in roll-axis rotation exist since there is the rotation axis in the drone, the projection image is also inclined by the rotation of the drone. The translation parameters $t_{y_{roll}}$, $t_{z_{roll}}$ in Fig. 3(a) can be estimated by $d\sin(\theta_{roll})$ and $d(1-\cos(\theta_{roll}))$, for each. Fig. 3(b) shows the geometrical model for rotation in the pitch-axis. In case of the pitch-axis rotation, the rotation itself contains the vertical shift, so there is the translation parameter in z-axis of the projected image $t_{z_{pitch}}$, which is estimated by $d\tan(\theta_{pitch})$. But, the translation parameter in the y-axis of the projected image $t_{y_{pitch}}$ is zero-valued. Fig. 3(c) describes the geometrical model for the yaw-axis rotation. Because the rotation itself contains the horizontal shift as similar to the pitch-axis rotation, there is the translation parameter in the y-axis of the projected image $t_{y_{yaw}}$, and it is computed by $d\tan(\theta_{yaw})$, and $t_{z_{yaw}}$ is zero-valued. Therefore, the translation parameters occurring when our drone-projector has rotations can be summarized by:

$$\begin{cases} t_{y_{roll}} = d\sin\left(\theta_{roll}\right) \\ t_{z_{roll}} = d(1-\cos(\theta_{roll})) \end{cases}$$
$$\begin{cases} t_{y_{pitch}} = 0 \\ t_{z_{pitch}} = -d\tan(\theta_{pitch}) \end{cases} \qquad (6)$$
$$\begin{cases} t_{y_{yaw}} = d\tan(\theta_{yaw}) \\ t_{z_{yaw}} = 0 \end{cases}$$

Therefore, the translation parameters can vary depending on the distance. As a result, the rotation matrices for roll, pitch, and yaw axes can be expressed by:

$$H_{roll} = \begin{bmatrix} \cos(\theta_{roll}) & -\sin(\theta_{roll}) & d\sin(\theta_{roll}) \\ \sin(\theta_{roll}) & \cos(\theta_{roll}) & d(1-\cos(\theta_{roll})) \\ 0 & 0 & 1 \end{bmatrix}$$
$$H_{pitch} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{pitch}) & -d\tan(\theta_{pitch}) \\ 0 & \sin(\theta_{pitch}) & 1 \end{bmatrix} \qquad (7)$$
$$H_{yaw} = \begin{bmatrix} \cos(\theta_{yaw}) & 0 & d\tan(\theta_{yaw}) \\ 0 & 1 & 0 \\ -\sin(\theta_{yaw}) & 0 & 1 \end{bmatrix}$$

Finally, the stabilization model H^* can be represented by inverse matrix of the transformation matrix defined in Eq. (1).

$$H^* = H^{-1} \qquad (8)$$

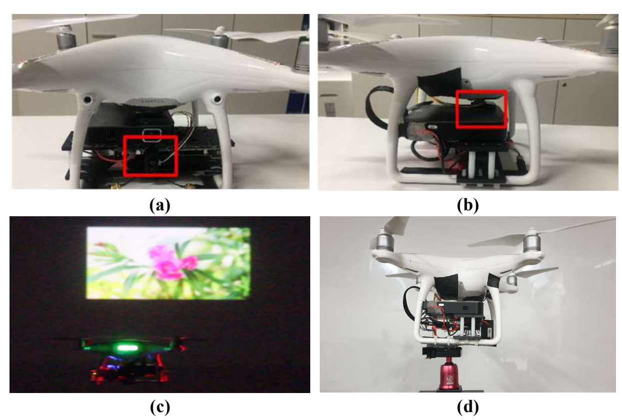


Figure 4. Our experimental setting. (a) Front view of the proposed drone-projector, (b) Its side view. (c) Shown in an actual flight. (d) The experimental setting for assessment. (The red rectangles indicate the location where the sensors are placed (a) LiDAR, (b) AHRS).

	Frame 1	Frame 2	Frame 3	Frame 4
Stabilization-OFF				
Roll, Pitch, Yaw	**2.08°, 2.16°, 0.78°**	**-18.26°, 0.69°, 1.13°**	**-23.30°, 14.05°, -5.78°**	**12.69°, -2.70°, 6.21°**
Stabilization-ON				
Roll, Pitch, Yaw	**2.03°, 0.55°, -1.07°**	**-11.04°, 0.22°, -0.13°**	**-4.08°, 19.42°, -6.24°**	**-0.35°, -2.48°, 2.16°**

Figure 5. Visual comparison of stabilization results of the projected image during flight.

Experimental Result

Experimental Condition

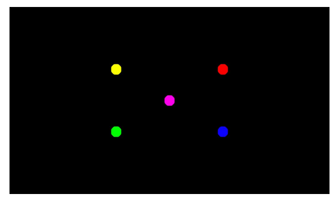
The proposed drone-projector consists of a small drone without a mounted camera, DLP projector, and AHRS and LiDAR sensors to measure the flight information. Additionally, a computation board with quad-core calculates the stabilization model pixel-wise in order to compensate the distortions of the projected image. Fig. 4(a) and Fig. 4(b) show the proposed drone-projector respectively in front view and side view. Fig. 4(c) shows an actual projection test during flight at night. To evaluate the stability performance of the projected image, we use a controlled environment in Fig. 4(d) with a sample image in Fig. 6(a).

Stabilization Result

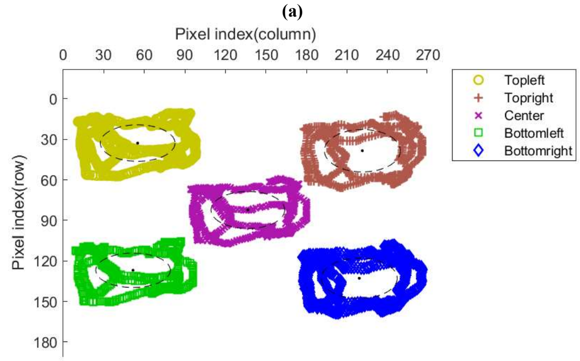
Fig. 5 shows a visual comparison of stabilization results of the projected image in flight. The projected images in stabilization-OFF are severely tilted and keystoned depending on the attitude of the drone-projector when it is compared to the projected image in stabilization-ON. Especially, at the second column in stabilization-ON, the projected image is still stabilized when the drone-projector has rotation with a large value in roll-axis.

Stabilization Assessment Result

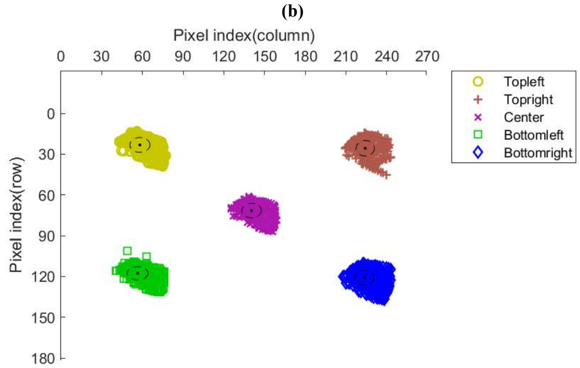
Before evaluating the stability performance of the projected image, the projection processes with stabilization ON and OFF are recorded using a stationary camera for 20 seconds using Fig. 4(a) which simulates the movement occurring while the drone-projector is flying. Fig. 6(b) and Fig. 6(c) show a comparison of trajectories based on representative points to check the stabilization of the projected image such as top-left, top-right, center, bottom-left, and bottom-right based on our prior work [9]. Additionally, the standard deviation (σ_{row}, σ_{col}) of the trajectory points corresponding to each position is computed as shown in Table 1. It shows the standard deviations (13.50, 27.64), (15.69, 28.13), (13.71, 27.28), (12.73, 27.60), and (14.90, 28.07) in stabilization-OFF case compared to (5.46, 7.41), (5.71, 6.74), (5.33, 7.21), (4.88, 7.70), and (5.43, 7.34) in stabilization-ON case.



(a)



(b)



(c)

Figure 6. Comparison of trajectories of representative points. (a) sample image [9]. (b) with stabilization-OFF. (c) with stabilization-ON.

Table 1. Standard deviation of trajectory points corresponding to the same position (unit: pixels)

Stabilization	Top-left	Top-right	Center	Bottom-left	Bottom-right
	$(\sigma_{row}, \sigma_{col})$				
OFF	(13.50, 27.64)	(15.69, 28.13)	(13.71, 27.28)	(12.73, 27.60)	(14.90, 28.07)
ON	(5.46, 7.41)	(5.71, 6.74)	(5.33, 7.21)	(4.88, 7.70)	(5.43, 7.34)

Conclusion

This paper investigated a drone-projector, so called a flying projector. It can serve as a moving display on the outer walls of high-rise buildings. However, the proposed drone-projector system inevitably suffers from vibration by propellers motors during flight, and it experiences distortions of the projected image such as tilt, keystone, and shift of the central point. In this paper, a method for stabilizing the projected image is introduced by a geometrical modeling. The experimental result based on our stabilization model shows that the standard deviations in stabilization-ON are smaller than those in stabilization-OFF. Moreover, in the visual comparison during actual flight, the distortions of the projected image due to the rotations of the drone-projector are seen significantly reduced. Nevertheless, while the proposed drone-projector is flying, the scaling of the projected image occurs frequently due to the distance change of the drone-projector to projection surface. For future work, we will extend the proposed stabilization model to take an account of stabilizing the scaling of the projected image.

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