Design and evaluation of antenna pointing control system onboard fixed-wing UAV to realize video transmission relay station

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\textbf{Abstract:} Unmanned Aerial Vehicles (UAV) are used for many services in various fields. We propose a video transmission relay system in which a fixed-wing UAV is used as a relay station. In order to establish the video transmission link, it is necessary to accurately point the antenna onboard a fixed-wing UAV to both the target ground station and the UAV for photography while making the UAV turn over the designated area. In this study, we propose a new antenna pointing control system, which uses a 2-axis gimbal to greatly reduce the attitude motion of the UAV, and describe evaluation results of the performance of the antenna pointing control system.

\textbf{Keywords:} Fixed-wing UAV, Antenna pointing control system, 2-axis gimbal, Video transmission relay station

\textbf{Classification:} Navigation, Guidance and Control Systems

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1 Introduction

Unmanned Aerial Vehicle (UAV) have recently been used to provide many kinds of services, such as monitoring crops and forest; inspecting tunnels, bridges, and buildings; measuring locations; transporting commercial goods; and relaying video and data [1,2]. Some are actually being provided, some of them are experimentally tried and under research and development. In response to the need for high image quality and long-distance transmission by UAV, frequencies in the 169MHz, 2.4GHz, and 5.7GHz bands have been legally established and are expected to be applied to various services.

The above services are often carried out by a multi-copter type UAV by using direct radio waves. The number of mountain accidents has increased in recent years, and debris flows and landslides caused by record heavy rains are happening frequently. In cases of providing search services for victims in mountainous areas or observing a disaster area, radio waves are often blocked by complex terrain and it is difficult for the UAV to receive the transmission image or the maneuvering command. In addition, victims and disaster areas should be observed from a long-distance point, several kilometers away, with a wide area well over 1 km square. Generally, a multi-copter type UAV can fly for only 20 minutes. Therefore, it is not appropriate for flying distant and vast areas.

Fig. 1. Video relay system image
Taking those situations into consideration, we propose a video transmission system by a fixed-wing UAV [3,4] appropriate for long flights (Fig. 1). The proposed system makes use of the 5.7 GHz band for a relay device. The fixed-wing UAV stays in a predetermined area by turning instead of hovering. This turning flight causes the direction of the antenna onboard the fixed-wing UAV to change in both elevation and azimuth angle. Therefore, to make these antennas point to the predetermined ground station and the UAV for photography, the fixed-wing UAV should be equipped with a 2-axis mechanical gimbal [5] so as to reduce the attitude motion of the UAV. The antenna is driven by the gimbal while it is influenced by the UAV motion. Besides as the UAV continues to turn, the command to the antenna direction continues to change [6].

In this paper we propose an antenna pointing control system, which consists of a fixed-wing UAV control system and an antenna driving control system driven by a 2-axis gimbal system. We describe complex equation of motions including the UAV and the gimbal and evaluation results of antenna pointing control error by computer simulations.

2 Antenna pointing control system

2.1 Configuration

An antenna pointing control system consists of two independent control systems: an antenna driving control system and a flight control system (Fig. 2). Since this antenna is attached to the bottom of the fixed-wing UAV, the attitude angle error of the fixed-wing UAV is directly added to the pointing direction error of the mounted antenna as shown in Fig. 2.

From the acceptable link margin, we determine the target error of the antenna pointing control in this system to be ±3 degrees on the transmitter side, and ±1.3 degrees on the receiver side.

2.2 Target command of the antenna pointing direction

In the proposed system, two pieces of 2-axis gimbals with directional antennas are
attached to the underside of the fixed-wing UAV. These point to the ground station and the target fixed-wing UAV independently by driving the azimuth and elevation of each 2-axis gimbal. In addition, the target command input to the control system is calculated based on the position, attitude of the fixed-wing UAV, and the position of the ground station and the UAV for photography. Moreover, this command is not a constant value and changes from moment to moment.

This time, assuming one 2-axis gimbal for transmission between the relay fixed-wing UAV and the ground station, the target commands for the elevation and azimuth of the 2-axis gimbal were derived using the positional relation in Fig. 1. The elevation angle target command $\theta_{GC}$ is shown in Eq. (1), and the azimuth target command $\psi_{GC}$ is shown in Eq. (2).

\[
\theta_{GC} = \sin^{-1} \frac{H \cos \phi + (R + D \sin \psi_p) \sin \phi}{\sqrt{R^2 + D^2 + H^2 + 2RD \sin \psi_p}} (1)
\]
\[
\psi_{GC} = \cos^{-1} \frac{-D \cos \psi_p}{\sqrt{(D \cos \psi_p)^2 + (H \sin \phi - (R + D \sin \psi_p) \cos \phi)^2}} (2)
\]

2.3 Equations of motion and design

The fixed-wing UAV used in the proposed system point the antenna using the 2-axis gimbals. To design the system, it is very important to derive equations of motions for the UAV and the gimbal.

Rotational motions around each axis of the fixed-wing UAV and 2-axis gimbal are derived as shown in Eq. (3). First three lines indicate the attitude motions of the UAV and the next two lines indicate the angle motions of the 2-axis gimbal.

\[
\begin{bmatrix}
I_{xx} & 0 & 0 & -I_{gy} \sin \psi_{AZ} & 0 \\
0 & I_{yy} & 0 & I_{gy} \cos \psi_{AZ} & 0 \\
-I_{gy} \sin \psi_{AZ} & I_{gy} \cos \psi_{AZ} & 0 & I_{gy} & 0 \\
0 & 0 & I_{gz} & 0 & I_{gz} \\
0 & 0 & I_{gz} & 0 & I_{gz}
\end{bmatrix}
\begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r} \\
\dot{\theta}_G \\
\dot{\psi}_G
\end{bmatrix} =
\begin{bmatrix}
L \\
M \\
N \\
T_GY \\
T_GZ
\end{bmatrix}
\]

\[
\begin{bmatrix}
I_{xz} \dot{r} + I_{xz}pq + (l_{zz} - l_{yy})qr + I_{gy}(r \dot{\theta}_G \cos \psi_G + \dot{\theta}_G \psi_G \cos \psi_G) - l_{gz} \dot{\psi}_G Q \\
-(l_{xx} - l_{zz})pr - I_{xz}(p^2 - R^2) + I_{gy}(\dot{\theta}_G \sin \psi_G + \dot{\theta}_G \psi_G \sin \psi_G) + I_{gz} \dot{\psi}_G G \\
I_{xz} \dot{p} - (l_{yy} - l_{xx})pq - l_{xz} qr - I_{gy}(p \dot{\theta}_G \cos \psi_G + q \dot{\theta}_G \sin \psi_G) \\
0 \\
0
\end{bmatrix} (3)
\]

From equations of motion, the attitude motion of the fixed-wing UAV and the angle motion of the 2-axis gimbals interacts with each other through angular accelerations. However, the amount of influence between two kinds of equations of motion is judged to be very small by using interference factor [7]. Therefore, it is found that the flight control system and the antenna driving control system can be designed independently.
3 Simulations

3.1 Conditions

Based on Eq. (3) and the control design method as the two independent control systems, the simulation of the antenna pointing control system was carried out using Matlab & Simulink. We assumed a fixed-wing UAV with a weight of 3.03 kg, a wingspan of 1.6 m, and a moment of inertia of $I_{xx} = 0.23$, $I_{yy} = 0.15$, $I_{zz} = 0.34$ kg·m² as the simulation conditions. The condition for the 2-axis gimbal was $I_{GY}, I_{GZ} = 0.01$ kg·m².

The turning radius and the altitude, turning flight speed and the horizontal distance between the UAV and the ground station were set to be 100 m, 100 m, 22 m/s, 3 km respectively. In addition, the wind disturbance was set to 3 m/s. Furthermore, noises for sensors were considered as random variables with a zero mean and a specified variance $\sigma^2$. The variances for attitude angles, altitude, beam direction, aircraft speed and GPS position were set to be $(0.5\ \text{degrees})^2$, $(0.2\ \text{m})^2$, $(0.01\ \text{degrees})^2$, $(0.17\ \text{m}/\text{s})^2$ and $(1\ \text{m})^2$, respectively.

3.2 Results

Fig. 3 shows results of the simulation under the above conditions. Fig. 3 (a) and (b) show the antenna pointing control error, and (c), (d), and (e) show the attitude angle profile of the fixed-wing UAV for relay. These antennas pointing control error are defined as in Eq. (4) and Eq. (5) using target command in Eq. (1) and (2) and antenna pointing direction $\theta_A$ for elevation and $\psi_A$ for azimuth.

$$\Delta \theta_A = \theta_A - \theta_{GC} \quad (4)$$
$$\Delta \psi_A = \psi_A - \psi_{GC} \quad (5)$$

$\sigma_{AE}$ and $\sigma_{AA}$ are standard deviation of antenna pointing control error. 

Fig. 3. Antenna pointing control error and UAV attitude
3.3 Evaluation of pointing control error
From results in Fig. 3, the standard deviation of antenna pointing control error was ±0.54 degrees for the elevation angle and ±0.67 degrees for the azimuth angle, even with the attitude fluctuation of the fixed-wing UAV.

Therefore, the target antenna pointing control error of the transmitter side and receiver side are satisfied for both elevation and azimuth angles.

4 Conclusion
We proposed a video transmission system using a fixed-wing UAV, and configured an antenna pointing control system consisting of the fixed-wing UAV and 2-axis gimbal. We also clarified the motion of the UAV and the 2-axis gimbal onboard antenna, and confirmed by simulation that the antenna pointing control error satisfied well with the required pointing control accuracy regardless of the attitude motion of the fixed-wing UAV. Based on these results, we will carry out experiments using an actual model airplane with a 2-axis gimbal onboard.

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